

**In the Eyes of a Rover: An Educational Game Exploring the Ubehebe Volcanic Craters,**

**Death Valley California, which Mimics the Traverse of a Rover**

By

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## Abstract

The game application, Hebebot: A Martian Expedition through a Terrestrial Analog, was developed for high school students and first year university/college students to promote planetary science, using analyzed data from the Ubehebe Volcanic Field in Death Valley, California. The Ubehebe Volcanic Field are hydrovolcanic landforms created by phreatomagmatic eruptions, which formed a series of maars, which last erupted in the Holocene. The Ubehebe craters are circular depressions, which resembles the crater rich landscape of Mars. The game illustrates how scientists interpret geologic features on Mars by using the techniques and theories used to interpret geologic features on Earth through analog sites. Maar craters resemble impact craters as both are open depressions below the ground surface. The objective of the game is to assist the student participants to identify the origin of the craters, whether they are volcanic or impact. The student participants identified the craters as maars. Photographic images including panoramas and MAHLI images, geochemical analysis- XRF, and petrographic images used to develop the game proved that the craters are maars formed by phreatomagmatic explosions.

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## Abbreviations

APXS	Alpha Particle X-ray Spectrometer
BREB	Brock Research Ethics Board
CGEN	Canadian Geoscience Education Network
CSA	Canada Space Agency
EarthComm.	Earth System Science in the Community
EIPO	Education and Public Outreach
HiRISE	High Resolution Imaging Science Experiment
HISD	Houston Independent School District
HRSC	High Resolution Stereo Camera
IDD	Instrument Deployment Device
IGEO	International Geoscience Education Organization
ISW	Instructional Skills Workshop
IUGS-COGE	International Union of Geological Sciences Commission on Geosciences Education
K/T	Cretaceous/ Tertiary
MAHLI	Mars Hands Lens Imager
MS	Mossbauer Spectrometer
MER	Mars Exploration Rovers
MI	Microscopic Imager
Mini-TES	Miniature Thermal Emission Spectrometer
MOLA	Mars Orbiter Laser Altimeter
MSL	Mars Science Laboratory

NASA	National Aeronautics and Space Administration
NDFZ	Northern Death Valley Fault Zone
NSF	National Science Foundation
OSS	Office of Space Science
PANCAM	Panoramic Camera
ppm	Parts Per Millions
RAT	Rock Abrasion Tool
STEM	Science, Technology, Engineering and Mathematics
TAS	Total Alkali vs. Silica
TCPS 2: CORE	Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans Course on Research Ethics
TCPS	Tri-Council Policy Statement
THEMIS	Thermal Emission Imaging System
TXESS	Texas Earth and Space Science
US	United States
UTIG	University of Texas at Austin's Institute for Geophysics
Wt.	Weight
XPL	Crossed Polarized Light
XRF	X-Ray Fluorescence

# Chapter 1: Introduction

## 1.1 Purpose of the Thesis

This thesis intended purpose is to develop a game application for high school to first year university students which illustrates how scientists interpret the origin of geologic features on Mars based on data acquired from satellite imagery and rovers. The acquired data is processed by using the theories and techniques used to define geologic features on Earth. The specific game produced in this thesis focuses on the basis for distinguishing maars (a hydrovolcanic landform) from impact craters, both of which are found on Earth and on Mars. Terrestrial analogs are used to mimic the Martian environment where instruments and procedures are tested before a mission is operated on Mars. The game then asks students to solve a planetary science problem of the origin of the craters, whether they were created by a volcanic eruption or an impactor. This give the students an opportunity to interpret a geologic feature by using the data provided. This thesis also includes descriptive data on an alluvial fan in appendix A that may be used in a future expansion of the game.

## 1.2 Exploring Mars using Earth

Planetary geologists reconstruct the surface of Mars by using the knowledge and processes of Earth's landforms, because Mars' surface is inaccessible for human exploration (Carr, 2006). Satellite and orbiters captured aerial images of Mars' surface, which are comparable to landforms on Earth. The Mariner 9 (November 1971) was the first orbital mission to Mars to successfully capture and share photographic images of the geologic landforms of the planet (Carr, 2006). In 1976 National Aeronautics and Space Administration's (NASA) Viking

Project landed two identical spacecrafts, each consisting of a lander and an orbiter: the Viking 1 and Viking 2 (Soffen, 1976). The Viking 1 lander landed on the western slope of Chryse Planitia, on July 20, 1976, and the Viking 2 lander landed at Utopia Planitia on September 3, 1976 (Soffen & Snyder, 1976). Information collected from the Mariner 9 radio occultations, stereo and photoclinometric observations, ultraviolet spectrometer and the Viking 1 and 2 Orbital images were combined into digital terrain models (Smith, D. E., Zuber, M. T., Solomon, S. C., Phillips, R. J., Head, J. W., Garvin, J. B., & Lemoine, F. G., 1999). The models of the Martian surface were made from Earth based radar ranging (Smith et al.). This information was used to divide Mars into the northern low plains and the southern cratered highlands. The orbital images showed high elevated areas of volcanoes, canyons, cratered areas, fluvial patterns, and low-lying areas, including lava plains (Soffen, 1976).

After years of exploring Earth, one way to understand the origin of a planet is to study the volcanic landforms. Volcanoes give information of the internal conditions of the Earth's mantle and the lithologies of the outer surface. Information is understood from the physical properties of the erupted materials and the volcanic landforms, all determine the style and nature of the eruption (de Silva & Lindsay, 2015). The Mars Orbiter Laser Altimeter (MOLA) is an instrument on the Mars Global Surveyor spacecraft which captures high-resolution measurements of the topography of Mars. The doppler tracker on the spacecraft has determined the planet's crustal composition (Zuber et al., 2000). Understanding the crustal composition of Mars elucidate the formation of the southern highlands of the Tharsis province and the northern low lands. The differences in crustal structure among the volcanoes of the Tharsis province reflect variations in magma composition, eruptive properties, and the structure of the lithosphere (Zuber et al., 2000). The various volcanic types are identified on Mars through the diverse

volcanic features. Mars volcanic landforms show evidence of predictable magma eruptions, phreatomagmatic eruptions forming both monogenetic and polygenetic landforms (Broz & Hauber, 2013).

Like on the Moon and Earth, Mars has many craters which were created by impacts from cosmic debris. Captured images taken by orbital spacecraft of Mars allow the examination of craters' size, range and their degradational states. The data provide observations of the geology and the morphology of the craters. Remote sensing techniques of gamma- and x-ray detectors, and magnetometers taken by spacecrafts examined the spectral properties of Mars. These observations are compared to the range and classifications of the impact craters on the Moon and Earth (Carr, 2006).

Jones, (1974) agrees that the degradation of certain features on the Martian surface can be attributed to the erosion, flooding and fluvial processes which occurred. These examples include channels, non-eolian crossbedding in alluvial fan deposits, and gravel deposits.

Comparing the images of the Martian landform features to the different geologic features of Earth could go no further, since information of the composition of the Martian soil was lacking. More information was needed to interpret the composition of the soil, which would indicate whether a volcano was silicate rich, basaltic, felsic, or whether the magma was sulfur rich or ice rich (McSween et al., 2003). Also, geochemical analysis of the soil can indicate whether a crater was created by a volcanic eruption or a cosmic impactor.

### 1.3 Rovers on Mars

It was necessary to have a device that could move around on the Martian surface and this requirement led to the development of a robotic vehicle called a rover (Copper, 1998). A rover can travel across the Martian terrain while it collects data, such as images and chemical analyses.

On July 4, 1997, Pathfinder, that included the Sojourner Rover, landed on Mars and began to explore (Copper, 1998). The Sojourner rover explored Ares Vallis, an area close to the landing site in Chryse Planitia (Matijevic et al., 1997). Alpha Proton X-Ray Spectrometer (APXS), collected the geochemical data of the soil composition (Copper, 1998). This led to the discovery that the rocks at the Ares site were pebbles derived from conglomerates. This suggested that water existed for conglomerates to be formed. Pathfinder landed on a flood plain at Ares Vallis. The surface is categorized as a depositional plain, covered with sedimentary deposits of sub angular to sub rounded pebbles, cobbles, and boulders. The disturbed soil contained elevated levels of sulfur mixed with fragmented basaltic materials from volcanoes, while the unaltered rocks contained low levels of sulfur (Carr, 2006). Sojourner helped scientists understand Mars' history of floods, erosion and fluvial activities (Matijevic et al., 1997). This example of the capabilities of the rover demonstrates the depth of knowledge deducted from the rover's operations.

The geologic makeup of Mars was further examined by other sophisticated rovers such as the Opportunity and Spirit Mars Exploration Rovers (2004) and Mars Science Laboratory (MSL) Curiosity Rover (2012) and previous rovers are listed/ included in Appendix B.

### 1.3.1 NASA 2020 Mars Mission

The Mars 2020 rover mission is scheduled for launch in July 2020. The rover will rely on the successful configurations of the Mars Science Laboratory Rover, Curiosity. The Mars 2020 mission intended purpose is to seek the signs of past life on Mars and to prepare samples in a cache to be brought back to Earth on a future mission. The rover is equipped with seven new scientific instruments and an advanced robotic system which will collect and seal the samples in the cache (Williford et al., 2018).

The ideal Mars 2020 landing site features the geologic diversity needed by the scientists who are waiting on the return of the future samples in the cache. The agreed site for landing the rover is a delta at Jezero Crater. Orbital data from Jezero Crater show the lithology as a diverse watershed, which provides evidence for subaqueous sediment deposition. Scientists believe that this site suits the set objectives to retrieve evidence of ancient life and prepare a cache of samples (Williford et al., 2018).

#### 1.4 Relevance to education

There is a need to educate the younger generations of the many opportunities and disciplines in Earth Sciences. The growth and depth of planetary science has increased sporadically. It is inevitable that the education system incorporates planetary science for the sustenance of space exploration. Educators are increasing hands on activities in their lesson plans in order to foster independent learning, critical thinking and making world connections. A student's curiosity leads to exploration. Students are fascinated about the world around them. Students communicate through writing, speaking and bodily movements to express and address science content. When all these are applied, the students can engage in scientific reasoning (Hapgood & Palincsar, 2006). It is of utmost importance that the education systems of both Canada and America make earth science an option among other sciences. The students educated in the discipline will continue to explore Mars in search of habitability, and future human exploration. Also, the job descriptions within the field will broaden while the job opportunities will increase, as more people work in the field.

Education increasingly includes video games as a learning tool. For example, 'Be A Martian' and 'Climate Kids' are science games developed by NASA for the Summer of Innovation Program (Dunbar, 2013). The use of technology has given learners a new way to

increase their knowledge and interest in the subject while having fun, even when the games are challenging.

In this thesis, the game application ‘Hebebot: A Martian Expedition through Terrestrial Analog’ is designed to introduce the geology of Mars and Earth to students at the high school and university levels. The game will bring an awareness of planetary science to students as an option for a university degree. Lesson plans aligned with the education curriculum introduce the content of the game. Players of the game will become familiar with comparable geologic features of maars (hydrovolcanic landform) and impact cratering formed on both Earth and Mars.

#### 1.4.1 Canadian Education System

With the increase in planetary research and scientific advancements, opportunities for learning Earth Science must be a part of the education curriculum. Advocates who try to add earth science to the school curriculum have faced many challenges. An overview of geoscience education across the world by King (2008) stressed that geoscience education will only progress when the curriculum is taught to every child. Orion & Ault (2007) agree that earth science can be sustainable only if the teachers are properly trained to teach geoscience. Teachers will need to attend professional workshops and courses to teach the different geoscience discipline.

Many people involved in the geosciences field understand the need to educate the younger generation for future sustainability. As a result, the International Geoscience Education Organization (IGEO) and the International Union of Geological Sciences Commission on Geoscience Education (IUGS-COGE) formulated a framework of the essentials that must be taught to students across the world. These organizations considered data from 34 countries, which included Canada and the United States (King, 2015). The syllabus provided opportunities for students to encounter principles in Earth Science that include: being curious about their



surroundings and understanding how things in nature come to existence, the role of science in society, scientific topics that might be of interest to them and understanding scientific contributions and their aim (King, 2015). Another attempt to incorporate Earth Science was made through the Canadian Geoscience Education Network, CGEN. The Canadian Geoscience Council founded this organization as a branch of the Canadian Federation of Earth Sciences (Vodden, 2009). This organization promotes and raises public awareness of earth sciences through improving the quality of education provided and public awareness to students and educators.

Other provinces incorporate Earth Sciences in their curriculum, but this thesis will focus on the curriculum taught by the Ontario province. Table 1-1 shows the topics in earth science taught at the different grade levels from the Ontario Curriculum (The Ontario Curriculum Grades 1-8: Science and Technology, 2007). Some of the topics are taught with other subjects like technology. The curriculum shows that Ontario students are taught the fundamental of earth and space systems. The secondary schools are in support of educating their students with programs which prepare individual students for their futures. Earth sciences is one area where the students can link what is taught to living in the environment.

The Ontario education curriculum expects teachers to develop instructional materials, assessments, and evaluations aligned with the mandated curriculum expectations (The Ontario Curriculum, Grades 11 and 12: Science, 2008). If the school curricula identify earth science as a science option, students will develop a liking for the discipline, as they realize how much Earth Science surrounds them (The Ontario Curriculum, Grades 11 and 12: Science, 2008). It is at the high school level that students lose interest in the subject as schools do not stress on the importance of the course as they do for the other natural sciences: Biology and Chemistry.

**Table 2-1.** Ontario's Earth and Space Science Curriculum

Grade level	Understanding Earth and Space Systems
Grade 1	Daily and Seasonal Changes
Grade 2	Air and Water in the Environment
Grade 3	Soils in the Environment
Grade 4	Rocks and Minerals
Grade 5	Conservation of Energy and Resources
Grade 6	Space
Grade 7	Heat in the Environment
Grade 8	Water Systems
Grade 9 Academic	The Study of the Universe
Grade 9 Applied	Space Exploration
Grade 10 Academic	Climate Change
Grade 10 Applied	Earth's Dynamic Climate

The Ontario Curriculum Grades 1-8: Science and Technology, 2007: The Ontario Curriculum, Grades 9 and 10: Science, 2008 (revised).

Twelfth grade students in Ontario are offered Earth and Space as a university introductory course. This course teaches the knowledge and skills needed to meet the entrance requirements for university programs. The course is taught in different strands (Table 1-2) (The Ontario Curriculum, Grades 11 and 12: Science, 2008 (revised)). Some high schools have adopted the earth science curriculum, but there are many who have not allowed earth science to be a choice among the other sciences, as earth science is not a mandate for graduation. This is a step forward, but one optional university preparation course is not enough to be an eye opener for students. The game application in this thesis will introduce students to planetary science in a fun and engaging way in order to entice them the processes of space exploration. Earth Sciences topics must be accepted as a traditional science at all grade level schools in Canada.

**Table 1-2.** Earth and Space Science Strands taught at Grade 12

Course	Strand B	Strand C	Strand D	Strand E	Strand F
Earth and Space Science, GRADE 12, University	Astronomy (Science of the Universe)	Planetary Science (Science of the Solar System)	Recording Earth's Geological History)	Earth Materials	Geological Processes

The Ontario Curriculum, Grades 11 and 12: Science, 2008 (revised).

The Canadian Space Agency (CSA) is a vibrant organization which contributes to space exploration especially in robotics. CSA partners with other space agencies in exploration, human spaceflights, communications and the development of science for Canada and other countries. Canada is determined to be a part of the global space programs through their support to researchers and robotics programs lead by CSA. It is important to incorporate and expose young Canadians to the operations and opportunities of CSA (Piedboeuf & Dupuis, 2003). CSA is determined to open education opportunities and career opportunities to young eager Canadians.

Canadian schools and parents who wish to expose their children to space exploration can visit the CSA website for a wealth of information. There are classroom activities, individual activities with the available instructions and printouts, multimedia resources and a link to request guest speakers and astronauts for classroom appearances. There are opportunities for the youth to get involved beyond the classroom, for example the Junior Initiative Campaign 2020. Students can apply and if accepted they get the opportunity to fly to the head quarters in Saint-Hubert, Quebec to be a part of the Astronaut Camp Summer 2020 (Canadian Space Agency, 2019).

#### 1.4.2 United States Education System

Some states within the United States of America include Earth Sciences in their curriculum, but it is not a mandate for graduation, therefore some school districts are not obligated to teach the subject. This thesis will elaborate on teaching Earth Sciences in the Houston Independent School District, Houston Texas. This district is my former place of employment as a Science teacher.

Table 1-3 shows the earth science expectations taught at the different grade level in Houston Independent School District (HISD). Students are taught the fundamentals of earth in grades one through eight.

In Texas, Earth and Space Science is an option for a capstone course. The University of Texas at Austin’s Institute for Geophysics (UTIG) has supported capstone by introducing the Texas Earth and Space Science (TXESS) Revolution. TXESS supports teachers by providing teacher professional development projects that equip them with the content and tools to teach this course (Ellins et al., 2013). Table 1-3 shows the earth science expectation used by high school students to develop their capstone project. Earth science is not taught as a mandatory science for high school graduation, therefore students tend to lose interest in the subject, making it less likely to pursue a degree in college.

**Table 1-3.** Houston Independent School District Science Curriculum (2019-2020)

Grade Level	Earth Science Expectations
Grade 1	SCI.1.7A Observe, compare, describe, and sort components of soil by size, texture, and color. SCI.1.7B Identify and describe a variety of natural sources of water, including streams, lakes, and oceans. SCI.1.8B Observe and record changes in the appearance of objects in the sky such as the Moon and stars, including the Sun. SCI.1.8C Identify characteristics of the seasons of the year and day and night.
Grade 2	SCI.2.7A Observe, describe, and compare rocks by size, texture, and color. SCI.2.7B Identify and compare the properties of natural sources of freshwater and saltwater. SCI.2.7C Distinguish between natural and manmade resources. SCI.2.8C Observe, describe, and record patterns of objects in the sky, including the appearance of the Moon. SCI.2.8A Measure, record, and graph weather information, including temperature, wind conditions, precipitation, and cloud coverage, in order to identify patterns in the data.
Grade 3	SCI.3.8A Observe, measure, record, and compare day-to-day weather changes in different locations at the same time that include air temperature, wind direction, and precipitation. SCI.3.7A Explore and record how soils are formed by weathering of rock and the decomposition of plant and animal remains. SCI.3.7B Investigate rapid changes in Earth’s surface such as volcanic eruptions, earthquakes, and landslides. SCI.3.3B Represent the natural world using models such as volcanoes or Sun, Earth, and Moon system and identify their limitations, including size, properties, and materials. SCI.3.8B Describe and illustrate the Sun as a star composed of gases that provides light and thermal energy. SCI.3.8C Construct models that demonstrate the relationship of the Sun, Earth, and Moon, including orbits and positions. SCI.3.8D Identify the planets in Earth’s solar system and their position in relation to the Sun.
Grade 4	SCI.4.8B Describe and illustrate the continuous movement of water above and on the surface of Earth through the water cycle and explain the role of the Sun as a major source of energy in this process.

	<p>SCI.4.3B Represent the natural world using models such as water cycles, stream tables, or fossils and identify their limitations, including accuracy and size.</p> <p>SCI.4.8A Measure, record, and predict changes in weather.</p>
Grade 5	<p>SCI.5.8B Explain how the Sun and the ocean interact in the water cycle.</p> <p>SCI.4.8B Describe and illustrate the continuous movement of water above and on the surface of Earth through the water cycle and explain the role of the Sun as a major source of energy in this process</p> <p>SCI.5.8A Differentiate between weather and climate.</p> <p>SCI.4.8A Measure, record, and predict changes in weather.</p> <p>SCI.5.7B Recognize how landforms such as deltas, canyons, and sand dunes are the result of changes to Earth's surface by wind, water, and ice.</p> <p>SCI.3.7B Investigate rapid changes in Earth's surface such as volcanic eruptions, earthquakes, and landslides.</p> <p>SCI.5.7A Explore the processes that led to the formation of sedimentary rocks and fossil fuels.</p> <p>SCI.4.7A Examine properties of soils, including color and texture, capacity to retain water, and ability to support the growth of plants.</p> <p>SCI.5.8C Demonstrate that Earth rotates on its axis once approximately every 24 hours causing the day/night cycle and the apparent movement of the Sun across the sky.</p> <p>SCI.5.8D Identify and compare the physical characteristics of the Sun, Earth, and Moon.</p> <p>SCI.3.8D Identify the planets in Earth's solar system and their position in relation to the Sun.</p>
Grade 6	<p>SCI.6.6C Test the physical properties of minerals, including hardness, color, luster, and streak.</p> <p>SCI.6.10A Build a model to illustrate the compositional and mechanical layers of Earth, including the inner core, outer core, mantle, crust, asthenosphere, and lithosphere.</p> <p>SCI.6.10B Classify rocks as metamorphic, igneous, or sedimentary by the processes of their formation.</p> <p>SCI.6.10C Identify the major tectonic plates including Eurasian, African, IndoAustralian, Pacific, North American, and South American.</p> <p>SCI.6.10D Describe how plate tectonics causes major geological events such as ocean basin formation, earthquakes, volcanic eruptions, and mountain building</p> <p>SCI.6.11A Describe the physical properties, locations, and movements of the Sun, planets, moons, meteors, asteroids, and comets.</p> <p>SCI.6.11B Understand that gravity is the force that governs the motion of our solar system.</p> <p>SCI.6.11C Describe the history and future of space exploration, including the types of equipment and transportation needed for space travel.</p>
Grade 7	<p>SCI.7.8A Predict and describe how catastrophic events such as floods, hurricanes, or tornadoes impact ecosystems.</p> <p>SCI.7.8B Analyze the effects of weathering, erosion, and deposition on the environment in ecoregions of Texas.</p> <p>SCI.7.8C Model the effects of human activity on groundwater and surface water in a watershed</p> <p>SCI.7.9A Analyze the characteristics of objects in our solar system that allow life to exist such as the proximity of the Sun, presence of water, and composition of the atmosphere.</p> <p>SCI.7.9B Identify the accommodations, considering the characteristics of our solar system that enabled manned space exploration.</p>
High School	<p>ENVS.8A Analyze and describe the effects on areas impacted by natural events such as tectonic movement, volcanic events, fires, tornadoes, hurricanes, flooding, tsunamis, and population growth.</p> <p><b>Students use this expectation as a guide to build their capstone project.</b></p>

(Houston ISD Curriculum 2019-2020, 2019).

NASA's Office of Space Science (OSS) has made great strides in educating the next generation, through many K-12 programs. NASA uses Science, Technology, Engineering and Mathematics (STEM) to share and teach their objectives to students. NASA uses its missions, research programs, and the human resources of the space science community to boost Planetary Science to the public. Data from the missions are used in programs to engage students from secondary school through graduate school (Slater et al., 2009). NASA distributes grants to organizations and local school districts to educate both teachers and students in Planetary Science through STEM (Slater et al., 2009).

Table 1-4 shows a list of accomplishments of NASA Office of Space Science (OSS) Education and Public Outreach (E/PO) program within a seven-year period from 1995 to 2002. OSS is determined to educate and share NASA's missions and objectives with the public as they believe that this will boost America's economy and allow America to be the leaders in space exploration. The OSS E/PO program remains ongoing and evolving as they continue to inspire the next generation of explorers (Rosendhal et al., 2004).

**Table 1-4.** NASA OSS E/PO program accomplishments 2002

Areas of improvements	Accomplishments
Status	<ul style="list-style-type: none"> <li>• A major National Program within the 50 states</li> </ul>
Breadth	<ul style="list-style-type: none"> <li>• Over 100 OSS missions and programs</li> <li>• 900 OSS-affiliated scientists, technologists, and staff</li> <li>• 500 institutional partners</li> </ul>
Infrastructure	<ul style="list-style-type: none"> <li>• 180 science centers, museums, and planetariums</li> <li>• 40 precollege educational organizations school districts and boards</li> <li>• 24 minority colleges/universities</li> </ul>
OSS Money	<ul style="list-style-type: none"> <li>• \$35,000,000 E/PO program</li> <li>• 1/3 for formal education programs (educators and students)</li> <li>• 1/3 to informal education programs (exhibits, shows and planetariums)</li> <li>• 1/3 to public outreach activities (public lectures, star parties and Web sites)</li> </ul>
Foreign outreach	<ul style="list-style-type: none"> <li>• European and Japanese partners on the Cassini mission are translating E/PO materials and planetarium into their languages.</li> <li>• Most NASA E/PO products are available over the internet, for international access</li> </ul>

(Rosendhal et al, 2004)

According to the information in Table 1-1 and Table 1-3, the science curriculum in Ontario and HISD teach similar science topics. The depth and length of the individual lessons depends on the school and the school districts. For example, in Houston, there is the Johnson Space Center and Space Center Houston, therefore some HISD schools spend more time and resources on topics related to space.

### 1.5 Importance of the Lesson Plans

This thesis educational goal is to allow students to play the game Hebebot: A Martian Expedition to a Terrestrial Analog. The game involves how scientists interpret geologic features using the Ubehebe craters in Death Valley California mimicking a rover on Mars. The expectation is for students to identify how scientists distinguish impact craters and volcanic craters. To distinguish these two types of craters, students must be knowledgeable of the characteristics and processes of each geologic feature. Before the game, students must complete three lessons which are designed to teach the morphology of maar volcanoes, impact craters and the operations of a rover.

The primary purpose of assessment and evaluation is to confirm that learning took place. Assessments also serves as a guide that teachers use to re-teach. The game Hebebot: A Martian Expedition to a Terrestrial Analog, is an assessment tool that conveys that teaching and learning took place. Each lesson has objectives that prepare the students with the necessary content for the game. Lesson plan 1 Learning Expectation: To determine the factors affecting the appearance of impact craters. Lesson plan 2 Learning Expectation: Students will be able to illustrate and explain the key features of the maar craters. Lesson plan 3 Learning Expectation: Students will learn the challenges of operating a planetary rover by using a hands-on simulation.

The lessons will follow a lesson plan format from the University of Toronto, 2018. The lesson is taught using the Instructional Skills Workshop (ISW) format; Bridge-In (this is the first part of the lesson, where the teacher shares or demonstrates something which gets the attention of the audience-), Pre-Assessment (finding out how much the audience know about the subject), and Participatory Learning (the strategies used to teach the new material)( ISW Handbook for Participants, 2006).

The testing of the game application in this thesis required authorization by Brock Research Ethics Board. Brock Research Ethics Board (BREB) ensured that this research is conducted under the support or within the jurisdiction of Brock University. The Research Ethics Board application provided information that explained the process of the study, copies of consent forms to the students, seeking their permission to be a participant the study. Also, the application showed sufficient information of the benefits of the study and the intended purpose of the data collected in the questionnaire (Appendix C). One requirement which accompanied the application was the certificate of Completion of the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans Course on Research Ethics (TCPS 2: CORE); an online panel on Research Ethics. After the application was accepted, the study was conducted.

#### 1.5.1 Details of the Lessons

The lessons are designed to provide students with sufficient background knowledge on maar volcanoes, impact craters and the rover. The lessons are taught through power-point presentations with small video clips and hands on activities. There is a worksheet to be completed during the lessons.



The objective of lesson 1 is to determine the factors affecting the appearance of impact craters. The power point presentation used to teach this lesson is in (Appendix D). Table 1-5 shows the information shared during the lesson on impact craters.

The objective of lesson 2 is to illustrate and explain the key features of a maar volcano. The power point presentation used to teach this lesson is in (Appendix D). Table 1-6 shows the information shared during the lesson on maar volcanoes

Lesson 3 provides students with an understanding of the purpose of Mars' rovers and how the rovers make observations and collect data from the planet's surface. This lesson allows students to use the rover in the game and it is taught through a power-point presentation and a group activity on the operations of the rover. The power point presentation used to teach this lesson is in (Appendix D). Table 1-7 shows the information shared during the lesson on the rover's operations.

**Table 1-5.** Information taught during the lesson on Impact Craters

Slide	Sequence of information
1	The students identify the features in the pictures. The images are impact craters on the Moon and Mars.
2	Background information on impact craters
3	Examples of impact craters on Earth including the theory of the asteroid which destroyed life on earth including the dinosaurs.
4	Students create a hypothesis of what affects the appearance of impact craters. Students look at a video which demonstrates what affects the appearance of impact craters. The students complete a worksheet during the video.
5	Small group discussion after the video. The students find out the factors which caused the appearance of impact craters.
6-7	Describe the features of impact craters and class discussion.

**Table 1-6.** Information taught during the lesson on Maar

Slide	Sequence of information
1	Identify which image is a volcano.
2	Checking for prior knowledge: what happens when heated oil is mixed with water?
3	Background information on maar volcanoes
4	Video clip to reenact a phreatic explosion Video clip of an Icelandic eruption
5	Maar formation activity with a partner
6	Describe the maar features

**Table 1-7.** Information taught during the lesson on the rover's operations

Slide	Sequence of information
1	Students discuss how the rover picks up the rock after showing a picture of a rover and a rock.
2	Introduction to Mars rovers and NASA's objectives in exploring Mars.
3-4	Martian rover 'Curiosity'
5	Scientific instruments on the rover
6	Factors affecting the rovers on Mars
7	Activity to find out the skills needed to operate a rover. Class discussion of the lesson

## Chapter 2: Using Earth analogs for interpreting geologic features/landforms on Mars

### 2.1 Introduction

Analog experiments on Earth provide a new paradigm for interpreting geologic features on Mars. A terrestrial analog is an environment on Earth with similar physical attributes to another planetary environment (Farr et al., 2002). These analogs provide an opportunity for geologists to study features on Earth in order to understand the processes of which these landforms were formed. When these similar landforms are seen on Mars it is inferred that they were formed by the same processes. Analog field sites on Earth are often in very remote, inhospitable environments, extremely arid/dessert, extremely cold/ polar altitudes. These locations are chosen because these are the environments comparable to Mars in the past or Mars at present.

The Mariner 9, the Viking 1 and Viking 2 spacecrafts provided a wide range of imagery of the Martian surface features. These images include canyons, volcanoes, channels, gullies, lava plains and craters (Soffen, 1976). In-depth imagery of Mars was taken by other orbiters and rovers (Opportunity, Spirit and Curiosity) over the years (2004-present) (Williford et al., 2018). Recognition of features on Mars that resemble features on Earth allows scientists to infer the processes which might have taken place on Mars.

Previous Mars missions under the Mars Exploration Program were designed to "Follow the Water" (Squyres et al., 2004). The evidence of a wet Mars in the past includes: ice caps at the north and south poles, surface features that suggest that ancient floods took place in the past, water trapped in icy dirt and volcanic craters formed by water ice and magma interaction

(Grotzinger et al., 2012). The information gleaned from studies on Earth are used as the framework to explain the processes that created Mars' landforms.

Scientists categorise the Martian features by using basic geomorphic classification used for Earth. Earth analogs provide studied examples that offer explanations for Martian features. Many landscapes on the Martian surface could have been produced by the same processes that form similar landforms on Earth, but maybe under different conditions (Thomas et al., 2005). There are terrestrial analog sites in various parts of the Earth. Research at these sites includes tectonics, volcanic, surface processes, polar processes, impacts, instrument and technology and laboratory modeling (Farr, 2004). The data from these research studies help interpret Mars and to prepare for future and ongoing missions. There are many analog sites which have been used or continue to provide data for Mars exploration. The following section briefly gives an account of the comparable environments with the comparable environment and landform features.

## 2.2 Examples of using features on Earth to interpret the surface of Mars

Chan et al., (2011) used images of the features of a small volcano in Snow Canyon State Park, Utah. The volcano resembles a circular depression, which is compared to a circular raised volcanic structure on the south flank of Pavonis Mons, Mars. Figure 2.1 shows the images of both features with a raised rim on a circular depression. Scientists study the basaltic flow, and cross cutting geometrics of the volcano in Utah to help analyze the Martian feature. It is hypothesized that the volcanic feature in (Figure 2.1 B), is not a closed circle because it eroded. Both features are said to be of volcanic cinder cones.

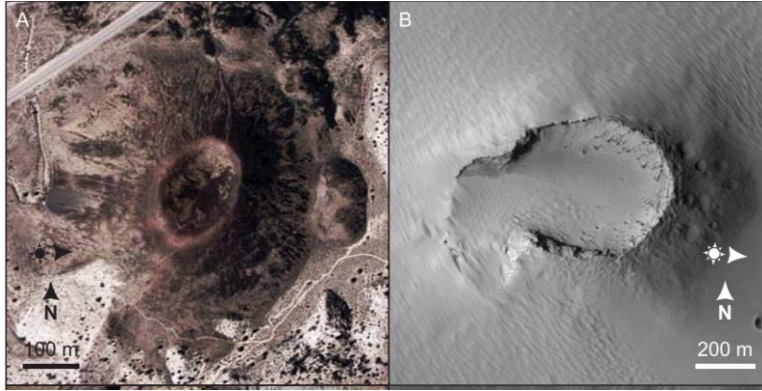


Figure 2.1. Volcanic structure from orbit. Image a) small volcano in Snow Canyon State Park Utah. Image b) HiRISE Image of volcanic structure on the south flank of Pavonis Mons, Mars (Chan et al., 2011).

Understanding the morphology of impact craters on Earth can be used to understand the origin and morphology of impact craters on Mars. Chan et al., (2011) used images (Figure 2.2) which captured the morphology of an impact crater in Utah and compared the data to an impact crater on Mars. Even though the geology of the land is not the same, the data analysed the structural discontinuities and folding caused by impact cratering and the ejecta layers of the craters to be similar. This comparison led them to believe that the Ada crater was an impact crater.

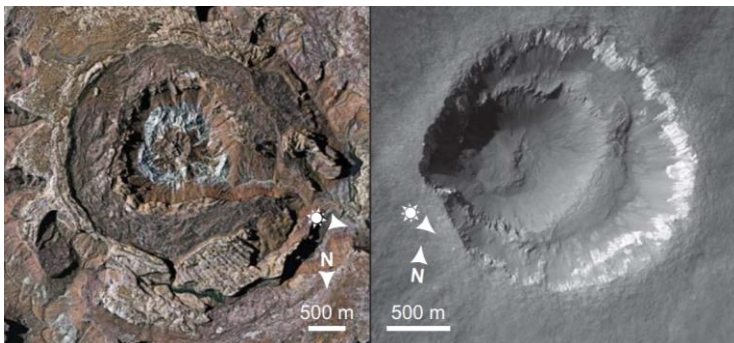


Figure 2.2. Impact craters from orbit. Image a) impact crater in Canyonlands National Park, Utah. Image b) HiRISE image of an impact crater in Ada crater on the southern edge of Meridiani Planum. The internal structure of the crater is seen (Chan et al., 2011).

Thomas et al., (2005) used images which captured the weathering and erosion features on in Australia and compared them with similar features on Mars. Mars has an abundance of loose soil and dust that suggests a desert environment. Rocks are weathered chemically and/or

mechanically, the exact weathering process might not be certain, but the morphological features of the rocks in both locations are very similar. “Insolation weathering” is the breaking up of a rock by heat fluctuation. This weathering process causes the rock to expand when heated and contract when it gets cooler. Examples of insolation are surface flaking of the rock and dirt cracking. Figure 2.3 shows an example of surface flaking on Earth and on Mars. “Surface flaking” is the loosening of the rock particles due to heat fluctuations. Figure 2.4 shows an example of dirt cracking on Earth and on Mars. “Dirt cracking” is the cracking of the surface of a rock due to heat fluctuations. There are lines showing the cracks in the rock. In the both images, smaller pieces of rocks look like they were broken off from the main rock, also loose sand surrounds the rock fragments. These features not only help to understand the physical processes of the rocks but also the atmospheric conditions of Mars (Thomas et al., 2005).

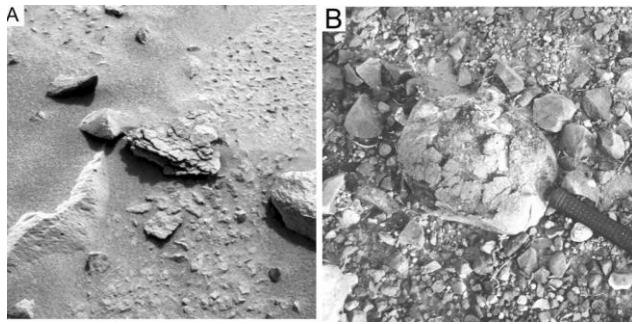


Figure 2.3. Insolation- surface flaking Image a) Image of rock taken from Gusev Crater on Mars. image b) weathered quartzite cobbles from the Mars analog site in South Australia (black hammer for scale) (Thomas et al., 2005).

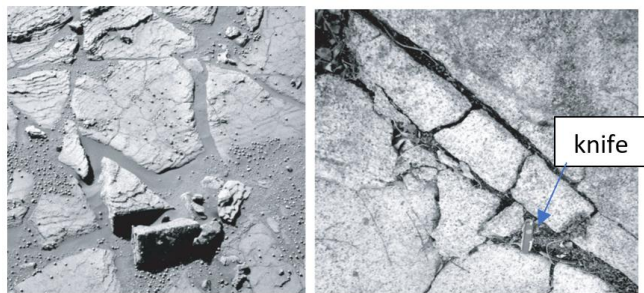


Figure 2.4. Insolation- dirt cracking Image a) Pamcam Image of rock taken from the rim of ‘Eagle’ crater on Mars. Image b) in weathered granite at Namadgi National Park ACT, Australia (knife for scale) (Thomas et al., 2005).

The action of the wind on rocks creates erosional features on Earth. “Aeolian fretting” is the removal of the fine-grained materials by wind from a surface of unconsolidated sediment and leaving behind the coarser sand grains aggregate leaving an erosion residual. Figure 2.5 shows an example of aeolian fretting on both Mars and Earth. (Thomas et al., 2005). In both images, loose sand surrounds what looks like thin sheets of coarse rock material.

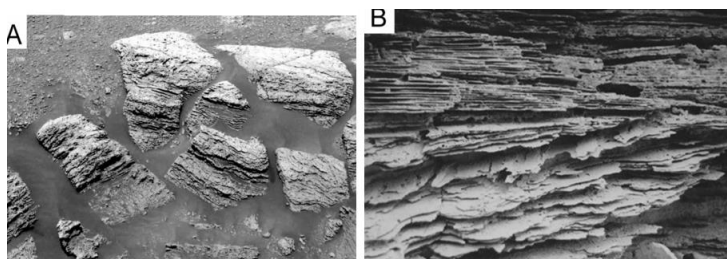


Figure 2.5. Fretting in rocks Image a) rocks on the rim of ‘Eagle’ crater captured by MER Pancam. Image b) rock fretting, Rottneest Island, Western Australia (Thomas et al., 2005).

Thomas et al., (2005) agree that some of the erosional and weathering features on Earth are used to explain how some of the similar features on Mars were formed. The same agents of erosion and weathering occur in the similar environments.

Reiss et al., (2011) studied the terrestrial gullies and debris- flow tracks on Svalbard in the Arctic ocean to determine whether fluvial and debris flow processes are responsible for the formation on gullies on Mars. This study was conducted by using High Resolution Stereo Cameras. A gully is a landform that is often created on a slope by running water, debris flow, grain flow or/and ice flow forming deep and wide ravines. The morphological features that are consistent with the gullies on Mars and on Earth are, there is a source area called the alcove, the erosional channel and the deposited area in the shape of a fan (Figure 2.6).

The climate in Svalbard is cold. Fluvial processes in this area after the snow melt is responsible for the formation of gullies. Mars had a wet past and there is ice in the cryosphere on

the planet, suggesting possible mass movement of the land. The gullies on Mars are formed by fluvial processes such as debris flow during periods of snow melt. Figure 2.7 shows the channels flowing into the gullies. The white lines point the levees and the black arrows point out the small fan deposits Image A and B are from Svalbard and image C is from Mars.

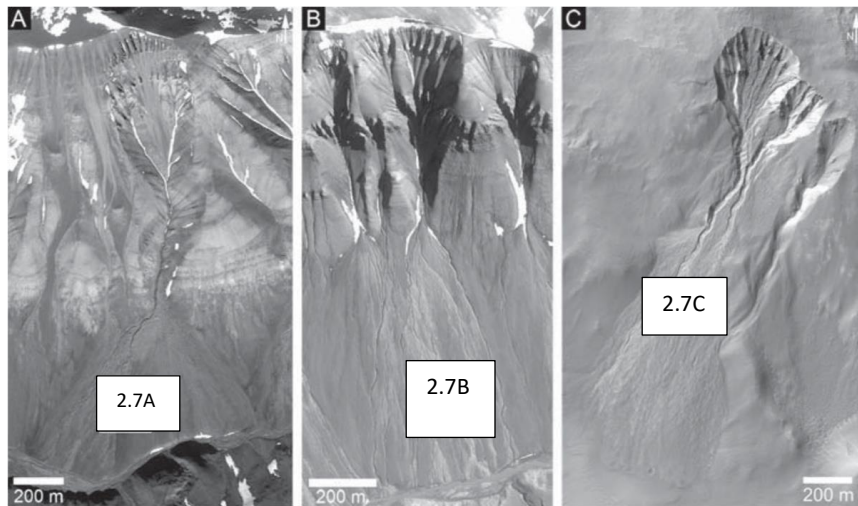


Figure 2.6. Images showing alcove area, gullies, channels, fan with deposits. White boxes show the locations of Figures 2.7 A–2.7 C. Image A and B are from Svalbard High Resolution Stereo Camera [HRSC-AX], 20 cm/pixel. Image C High Resolution Imaging Science Experiment [HiRISE] image 25 cm/pixel (Reiss et al., 2011).

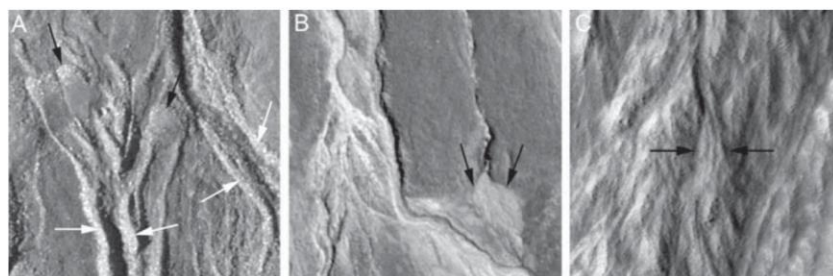


Figure 2.7. channels flowing into gullies. Image A and B are from Svalbard High Resolution Stereo Camera [HRSC-AX], 20 cm/pixel. Image C High Resolution Imaging Science Experiment [HiRISE] 25 cm/pixel (Reiss et al., 2011).

Scientists studied features on Ubehebe Crater, Death Valley that are described as tongue-shaped, debris lobes (200 meters long) at the base of the interior slope of the crater (Eyles & Daurio, 2015). Data retrieved in the form of geomorphological observations, sedimentological analysis of outcrops and a ground penetrating radar survey, show that the surface material was slumping due to seasonal snow during a period of ice age melting. This information of debris



lobes inside Ubehebe Crater are labeled as protalus ramparts and assist in the interpretation of impact craters on Mars. The data obtained from Ubehebe Crater share similarities with the cold paleoclimate of Martian craters and the formation of rampart cratering on Mars (Eyles & Daurio, 2015).



Figure 2.8. 200 meters debris lobes on the northeast slope of the Ubehebe Crater due to seasonal snow fall. In the image A is the large lobe and B is the small lobe (Eyles & Daurio, 2015).

### 2.2.1 Death Valley as a good analog field site for this thesis.

Death Valley is a well-studied and characterized desert environment with diverse geologic landforms. The geologic landforms in Death Valley infer an environment where water helped shape the geologic landforms. There are features which indicate Death Valley underwent periods of volcanic activities, fluvial processes, glaciation, weathering and erosion. Today Death Valley is dry and arid, with little precipitation and areas with little or no vegetation. Some geologic features in Death Valley are currently being altered by weathering and erosion. Orbital images of certain areas of Death Valley resemble the dry and barren environment on Mars.

The Ubehebe Volcanic Field, Death Valley is in a dry environment with evidence of phreatic eruptions in the past. The large depressions amidst the desert environment resemble craters on the Martian surface. The features in and around the craters support their formation by

volcanic processes. This analog site affords an opportunity to learn about hydrovolcanic features in a setting that is like that of Mars.

## 2.3 Scientific Question: Impact Crater vs. Volcanic Craters

### 2.3.1 Volcanic Craters

Most terrestrial volcanoes fall into one of the categories of conventional volcanoes: (shield volcanoes, cinder cones and stratovolcanoes/ composite volcanoes) and hydrovolcanoes. Conventional volcanoes are driven by magma and volatiles, while hydrovolcanoes are driven by extraneous water. Each type differs in terms of the tectonic setting, nature of its magma, the behavior of the erupted materials, the history of eruption, and the overall morphology of the volcano's landform (Carr, 2006). Volcanic eruptions are measured by the magnitude and intensity of the eruption. The magnitude is the total volume of erupted material in (mass kg or volume  $\text{m}^3$ ,  $\text{km}^3$ ) of gas, ash or lava. The intensity is the discharge rate of the magma in ( $\text{kg s}^{-1}$  or  $\text{m}^3 \text{s}^{-1}$ ) (Francis & Oppenheimer, 2004). Table 2-1 classifies the differences among conventional volcanoes.

**Table 3-1.** Summary of the differences between the three common classes of volcanoes

<b>Classifications</b>	<b>Composite volcano/Stratovolcano</b>	<b>Cinder cone volcano/ scoria cone</b>	<b>Shield volcano</b>
<b>Structure</b>	A conical shape with layers of ash and lava 8000 feet	A steep sided volcano consisting of tephra/volcanic debris 300-1,200 feet	A shield built from mostly fluid lava. Spreads horizontally
<b>Tectonic setting</b>	Zone of subduction Pacific Ring of Fire	Commonly found on the flanks of shield volcanoes and stratovolcanoes	Hot spots Spreading centers-divergent boundaries
<b>Eruption Style</b>	Explosive and effusive	Explosive	Effusive flows in all direction
<b>Magma type</b>	Very viscous Andesitic, rhyolitic and dacitic lava	No steam or little magma. Piles of rocks Basaltic lava	Less viscous Basaltic lava
<b>Examples</b>	Krakatoa, Mount Helens, Vesuvius, Mount Tambora	Paricutín in Mexico	Mauna Loa-Hawaii-55,770 feet beneath the ocean and 13,681 feet above sea level

Magma compositions determine eruption types. Magma compositions may change due to partial melting of the crust which forms a hybrid of contaminated magma (mafic magmas, intermediate magmas and felsic magmas). Properties of mafic magmas: water content <0.5 % volatile water, temperature 1250 °C, silica content 45-57 %, viscosity  $10^2$ -  $10^3$ Pascals (Francis & Oppenheimer, 2004). Properties of intermediate magmas: water content <1-3 % volatile water, temperature 800-1200 °C, silica content 57-70 %, viscosity  $10^3$ -  $10^7$ Pascals (Francis & Oppenheimer, 2004). Properties of felsic magmas: water content 4- 5 % volatile water, temperature 700-900 °C, silica content >70 %, viscosity  $10^8$ -  $10^{14}$ Pascals (Francis & Oppenheimer, 2004). Most silica rich magmas: rhyolites and dacites are generally explosive as they are less viscous, low temperatures and dissolved water: water dissociates in silicic magmas. Magmas which are not silica rich: andesites and basalts are generally less explosive or effusive

as they are more viscous, high temperatures and little dissolved water (Francis & Oppenheimer, 2004).

Fractional crystalization occurs when magma stagnates in the magma chamber, causing the magma to crystalize into different minerals at different temperatures forming different rocks. Mafic magma has a low viscosity, therefore olivine crystalizes first, as magnesium and iron sinks to the magma chamber. The olivine crystals mix with more silica to form pyroxene. As temperature decreases, pyroxene changes to amphiboles and amphibole to biotite. At the point where pyroxene crystallizes, plagioclase also crystalizes with the addition of calcium to form anorthite. Felsic magmas will form rocks such as feldspars and quartz in the presence of high amount of silica in more viscous magmas (Francis & Oppenheimer, 2004).

There are two types of eruptions, explosive eruptions and effusive eruptions. An explosive eruption is driven by gas, volatiles, and/or phreatic explosions projecting magma and tephra. Most stratovolcanoes are constructed by both explosive and effusive eruptions. An effusive eruption is the outpouring of lava out of the vent of the volcano with little or no explosiveness. Most shield volcanoes produce effusive eruptions.

The names of the different styles of eruptions are named after the names of volcanoes where specific eruptive behaviors have been observed. Some volcanoes experience one eruptive style during an active period, while some volcanoes experience various eruptive styles during an active period.

Volcanoes can further be classified by the different eruptive mechanisms seen in magmatic eruptions, phreatomagmatic eruptions and phreatic eruptions. The different magmatic eruptions types depend on the volatile content of the magma and the speed at which the magma rises. There are extremes in eruptive types of basaltic activity, passive effusion -Hawaiian style

to explosive- Plinian style. Effusive styles result from low gas contents forming vesiculated lavas. Explosive styles result from high gas contents and/or lack of ground water (Parfitt & Wilson, 1995).

**Hawaiian Eruptions.** Hawaiian eruptions are dominantly effusive basaltic flows rising at high speed. They are associated with the building of shield volcanoes and flood basalt plains. Lava flows from main vents as lava fountains or/and fissure vents as curtain of fire. Lava from the lava fountains solidifies before reaching the ground, the material builds up forming a cinder cone. Pu'u O'o, is a cinder cone on Kilauea which erupts continuously (Parfitt & Wilson, 1995).

**Strombolian Eruptions.** Strombolian eruptions are moderately explosive, which produces basaltic to andesite magmas rising at slow speed. This eruption is driven by the bursting of large gas bubbles in the viscous magma. Strombolian eruptions produce incandescent scoria, bombs and ash. The eruption can be very loud and short lived from a few minutes to a few hours (Parfitt & Wilson, 1995).

**Vulcanian Eruptions.** Vulcanian eruptions are moderate to violent ejecting solid fragments of cold rock or solidified magma. The eruptions are short lived. The magma can be andesite to dacite and is very viscous which makes it difficult for gas to escape and materials to be dispersed far from the vent. The eruptions produce more ash and less steam in a dark yellow eruption cloud. The pyroclastic flows show crystallization of rock fragments (Kennedy et al., 2005).

**Pelean Eruptions.** Pelean eruptions are violent outburst of volumes of pyroclastic flows—nuées ardentes, after the collapse of a dome. The collapse of the rhyolite, dacite, and andesite dome creates large amount of gas, dust, ash, and lava fragments being dispersed kilometers in the

air away from the vent. Also, pyroclastic flow (block and ash) surge down the flanks of the volcano at high speeds (Roobol & Smith, 1976).

**Plinian Eruptions.** Plinian eruptions are very explosive driven by large amounts of dissolved gases in the magma. The gaseous bubbles in the magma agglutinate on its way up the conduit, once they get big, they burst open moving at high speeds forming eruption column in the atmosphere. Distinct of Plinian eruptions are the sustained eruption columns stretching into the stratosphere (Carey & Sigurdsson, 1989). Plinian eruptions deposit ignimbrite from the eruption columns (Francis & Oppenheimer, 2004).

The classifications made for volcanoes were developed based on observations of subaerial volcanoes that were relatively easy to study. However, most of the volcanoes on Earth are found in submarine settings which are much less accessible than subaerial volcanoes. Over recent years there has been a growing interest in hydrovolcanoes which include submarine volcanoes, glacial volcanoes and subaerial volcanoes that are strongly influenced by magma/water interactions during volcanic eruptions. These volcanoes can produce phreatomagmatic eruptions that are very powerful and produce copious amounts of fragmented materials.

Hydrovolcanoes are not confined to just one class of volcano, they encompass all environments where water and magma mixes. The ratio of magma to water determines the type of hydrovolcano (Sheridan & Whletz, 1983). Figure 2.9 shows the types of hydrovolcanoes and their landforms.

Scoria cones are created by eruptions of viscous lava and little or no water. As lava enters the atmosphere, it cools and falls back as tephra or cinder. The cinder cone grows and piles more cinders on its slopes, taking the shape of a cone (Francis & Oppenheimer, 2004).

Tuff is considered consolidated volcanic ash (Brož & Hauber, 2013). Tuff rings are formed when magma interacts with ground water and the pyroclastic materials settle around the crater opening. Tuff rings are shallow, because of the fragmentation of the erupted rocks.

Tuff cones are steeper and smaller than tuff rings. The factors that determine whether a tuff ring or a tuff cone will form are the amounts of water and magma and their relative proportions, and the duration of the eruption. For a tuff cone to form, the erupted ash and magma must have more water than magma (Francis & Oppenheimer, 2004). Although the interaction of water and magma increases the explosive power of an eruption, if more water than magma escapes out of the vent of the volcano then less fragmentation occurs forming tuff cones. As seen in (Figure 2.9), the walls of tuff cones are steeper as the erupted materials fall close to the vent.

Pillow Lavas are produced by another type of hydrovolcano. Pillow lavas are very common but are not rarely seen to develop because they are formed in deep water. Pillow Lava eruptions are not explosive because of high water and magma ratio, and the confining pressure of the water. Little fragmentation occurs, as rapid cooling causes the magma to solidify at the base of the sea floor in the shape of a mound (Figure 2.9) (Francis & Oppenheimer, 2004). Scoria cones are formed with little or no water, the volcano flanks are steep formed from layers of ash and lava (Figure 2.9).

The determining factors of the presence of (subsurface water verses surface water) and the amount (depth) determines whether a scoria cone, tuff ring, tuff cone or pillow lavas forms. According to Figure 2.9, the less water: magma ratio allows the buildup of ash near the vent-scoria cone.

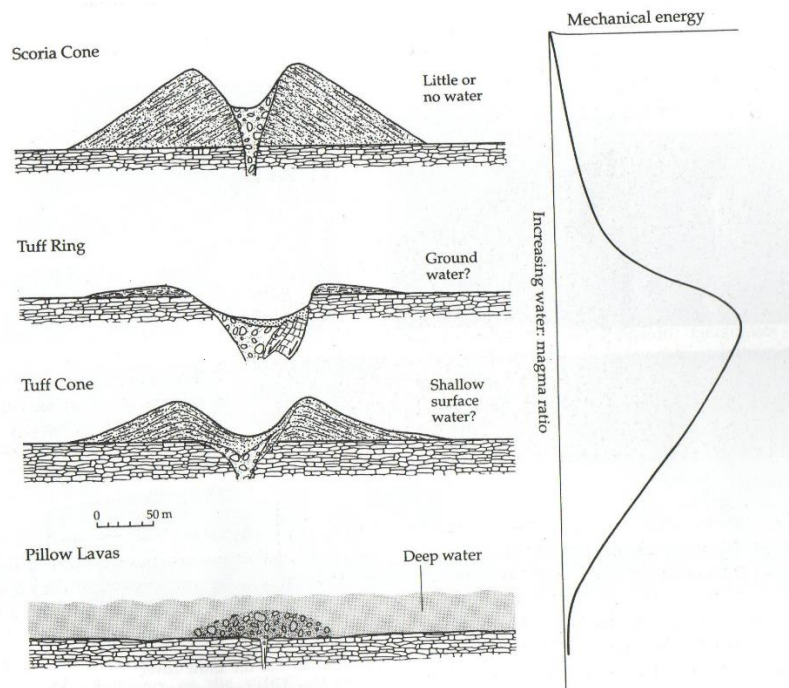


Figure 2.9. Cross section views of the different hydrovolcanic landforms. The images show the type of water reservoir, and the plot of the water to magma ratio and the mechanical energy (Francis & Oppenheimer, 2004).

### 2.3.2 Maar on Earth

Maars are hydrovolcanic landforms and the second most common volcano type on Earth (Valentine et al., 2017). A typical maar is formed after repeated explosions of water and magma interaction over a few days to a few years (Palladino et al., 2015). Maars are circular depressions which leave a crater in the ground. On Earth, most maars are buried, eroded, become lakes and/or are covered by vegetation, and are best preserved in arid climates. Most maars occur in volcanic fields of basic to ultrabasic basaltic composition of individual monogenetic volcanoes (Lorenz, 2003). Some maars are felsic in composition, but they are not as common as those of mafic composition (Ross et al., 2017). Maars are particularly difficult to identify based on surface morphology because they closely resemble impact craters that form by processes that are unrelated to volcanic eruptions. However, close inspection of such landforms on Earth provides clues for distinguishing maars from impact craters. The Ubehebe Volcanic Field in Death Valley,



California is an example of a mafic monogenetic volcanic field. “Monogenetic” meaning the result of a single magmatic episode (Champion et al., 2018).

Figure 2.10 is a schematic diagram of a typical maar. The maar crater can be as wide as <100 meters to over 2 kilometers in diameter (measured from the crest of the tephra ring) and can reach depths of 300 meters (measured also from the crest of the tephra ring) (Lorenz, 2003). After the eruptions have ceased, the infill of the maar crater is controlled by re-sedimentation processes-erosion, from the walls of the crater and surrounding tephra ring (Kurszlaukis & Fulop, 2013).

The diatreme is the area below the crater, extending meters to >1 km below the surface. The upper diatreme contains bedded diatreme facies of stratified pyroclastic deposits, post-eruptive sediments, dipping inward (White, 2011). The lower diatreme contains unbedded diatreme facies of pyroclastic materials that cut across bedded fills. During an eruption, the diatreme is filled with unconsolidated juvenile and lithic materials with water storing capabilities. Most of the water from erupted jets collapse into the crater and is recycled back into the system (White and McClintock, 2001).

The tephra rings are made up of pyroclastic deposits of bedded and cross-bedded tuffs and lapilli tuffs, these lithic rich deposits are often suggestive of eruptions dominated by discrete, short-lived explosions (Valentine et al., 2017). A key feature of the ejecta ring deposits is well-developed stratification which indicates multiple depositional events (White, 2011).

The root zone is the area below the diatreme above the feeder dike. The root zone is a chaotic zone because water from the aquifer or fault enters this area and causes an explosion. The area has clastic rocks, and marginal breccias. The wider the root zone, the less impactful the explosion on the country rocks, since the explosion cavity is shielded in the root zone (White,

2011). The feeder dike and feeder vent provide the magma to the system. The feeder vent stems from the feeder dike and spans to the crater floor.

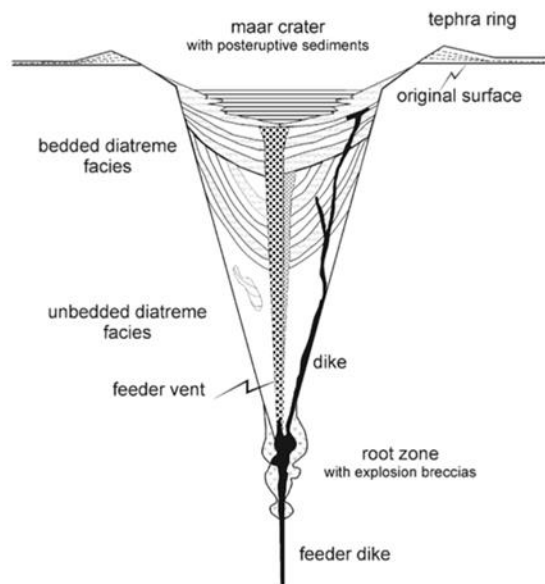


Figure 2.10. Schematic cross-section diagram of a maar-diatreme volcano showing its feeder dyke, root zone, cone shaped diatreme, feeder vents, the maar crater with its post-eruptive sediments (Lorenzo, 2003).

In this thesis, the maars of the Ubehebe Volcanic Field in the Death Valley National Park California, is the chosen field site (Figure 2.11, 2.12). The Ubehebe Volcanic Cluster are phreatomagmatic volcanoes (Figure 2.12), located at the north end of the Cottonwood Mountains. The magma-water interacted beneath the Tin Mountain which is composed of a thick, indurated Miocene conglomerate and sandstone (Fierstein et al 2017). Beryllium-10 dates the eruptions to have occurred 4300 years ago in the late Holocene (Fierstein et al 2017). Figure 2.12 shows the locations of the individual craters. Seven of the craters form the main group, with a north-south alignment 1.5 kilometers long, and five other craters erupted with an east-west alignment 500 meters west of the main crater group. There is also an isolated crater south of the east-west alignment (Fierstein et al 2017). These maars erupted through a layer of Miocene

fanglomerate and sandstone, which are now distributed as fragmented matrix and lithic clasts in all Ubehebe deposits (Fierstein et al 2017).

The largest and best known of this group of maars is Ubehebe Crater that is approximately 800 meters wide along a line trending north/south and 165 meters deep (Figure 2.12) (Fierstein et al., 2017). South of the big crater is a depression called the Amphitheater, which has southern, middle, and northern segments (Cagnoli & Russell, 2000). The second largest crater is Little Hebe Crater in the northern segment which is approximately 20 meters deep and 100 meters wide) (Figure 2.12) (Fierstein et al., 2017).

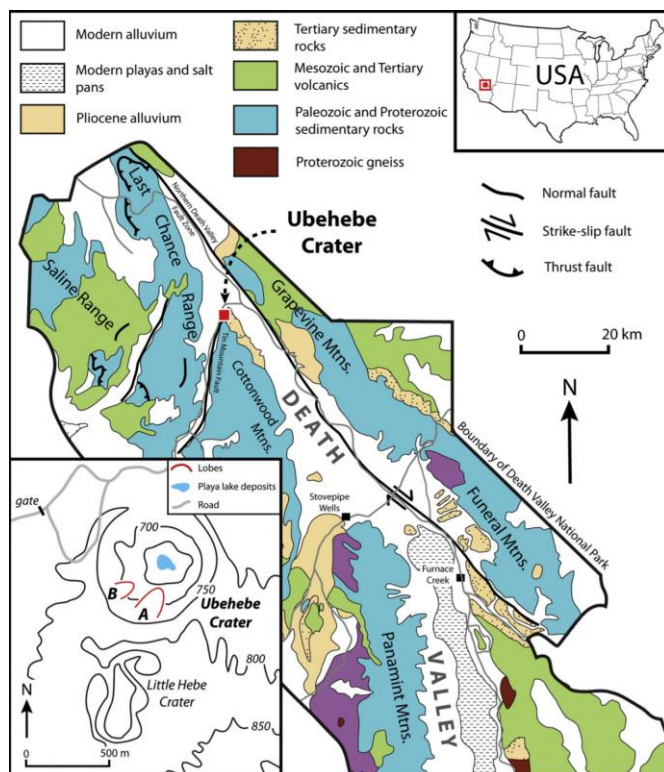


Figure 2.11. Geologic map of Death Valley, showing the location of the Ubehebe Volcanic craters, the Cottonwood Mountains, Grapevine Mountains, Northern Death Valley Fault Zone (NDFZ), Tin Mountain Fault (Eyles & Daurio, 2015).

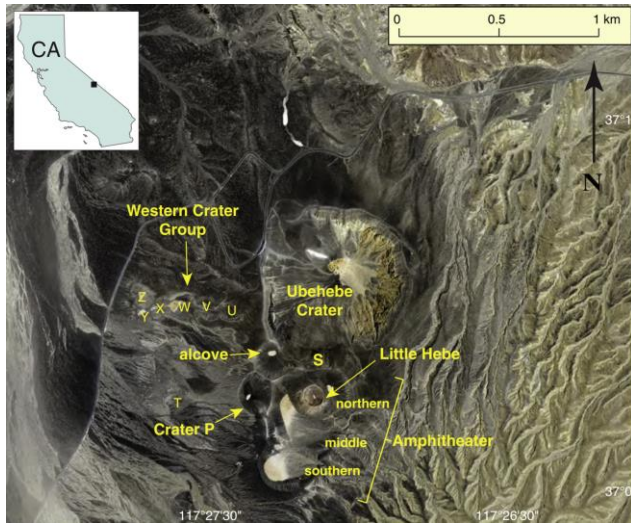


Figure 2.12. Image showing an aerial view of the location of each maar which make of the Ubehebe Volcanic Field, Death Valley California (Fierstein et al., 2017).

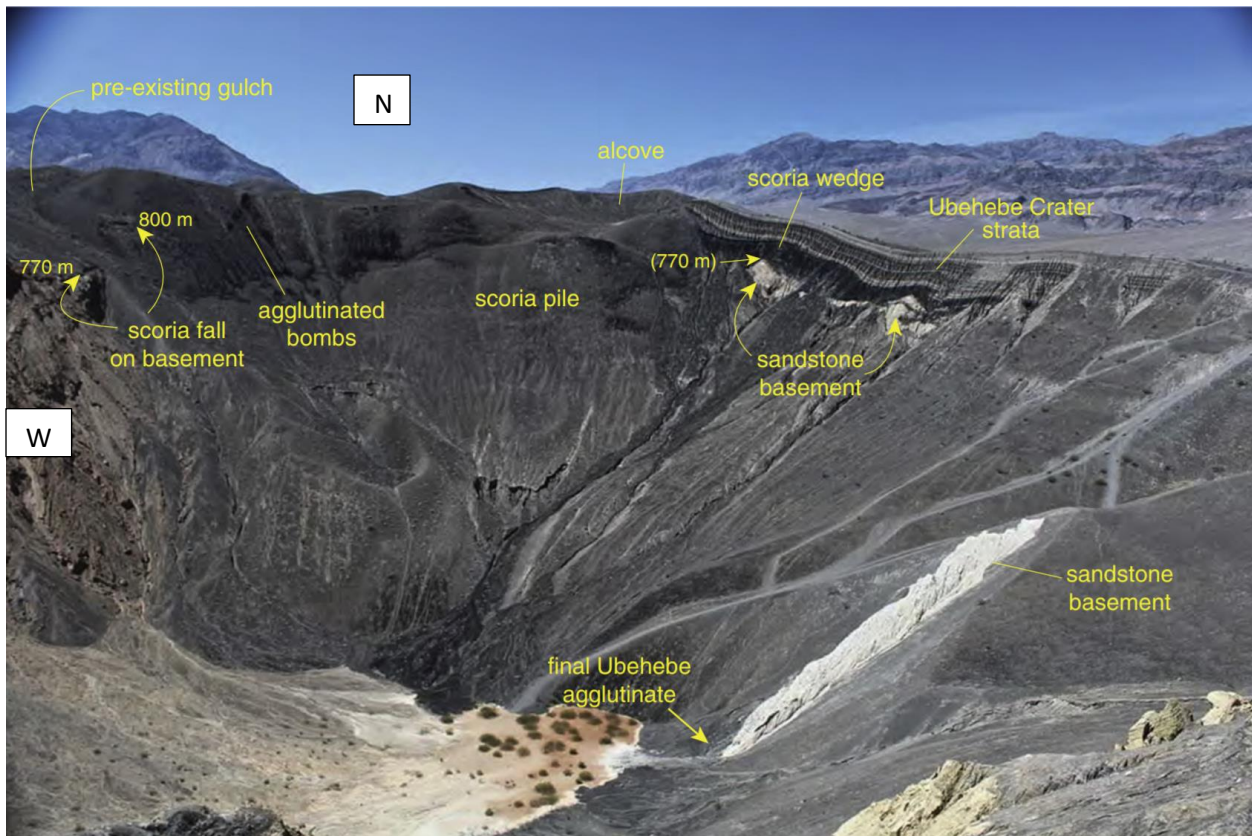


Figure 2.13. Image of the inside of Ubehebe crater, showing the features formed after the eruption and the deposited materials along the inner walls of the crater and at the bottom of the crater. North and west points are labelled (Fierstein et al., 2017).

Figure 2.13 shows the morphological features and the deposited erupted materials in the Ubehebe Crater (Fierstein et al., 2017). There is a scoria wedge on the east wall of the crater.

The scoria wedge is above a lightly colored sandstone basement as indicated in the image.

Above the scoria wedge, there are thin layers of black and tan pyroclastic ash fall deposits. On the northern side of the crater there are agglutinated bombs near the rim of the crater. The crater rims are very steep  $\sim 30^\circ$  angle, except for local areas on the western side which serves as an entrance into the crater due to the relatively low slopes. There is a scoria pile north of the crater. This crater shows all the features and deposits of a maar eruption (Fierstein et al., 2017).

### 2.3.3 Volcanic Craters on Mars

Mars is said to have had a very active past, including global volcanism during the Noachian period ( $>3.7$  Ga) which accounts for  $\sim 60\%$  of the morphology to be volcanic (Werner, 2009). Mars volcanism is associated with internal heat flow, no plate tectonics and low gravity (Werner, 2009). Satellite imagery show the diversity of volcanic landforms on Mars. Like Earth, there are volcanic landforms on Mars that indicate distinctive styles of volcanism (Caprarelli & Leitch, 2009). In the southern portion of the planet, the Tharsis and Elysium regions are the highlands whose morphologies are basaltic analogs to Hawaiian basaltic landforms. The Tharsis region remains the most active region on the planet (Werner, 2009). The Tharsis region is a huge volcanic bulge covering more than a fifth of the planet's surface, characterized by volcanic plains and shield volcanoes (Beuthe et al., 2012). This topographic rise is over 7 kilometers in height (Beuthe et al., 2012). In this region, the five largest volcanoes are Alba Mons, Olympus Mons, Ascraeus Mons, Pavonis Mons, and Arsia Mons, and seven smaller volcanoes are Ceraunius Tholus, Uranus Mons, Uranus Tholus, Tharsis Tholus, Jovis Tholus, Biblis Tholus, and Ulysses Tholus. Most of these volcanoes display features that are associated shield volcanoes with collapsed calderas (Robbins et al., 2011).

Some of the volcanoes on Mars indicate magma and ice interactions (phreatomagmatic eruptions). Hydro volcanism is believed to be active on Mars as, ice is present in the kilometer-thick cryosphere on Mars (Carr, 2006). The morphology of Mars indicates that water has occasionally erupted onto the surface and froze (Carr, 2006). Meresse et al., (2008) proposed that ice was present in the volcanic sills on Mars. Also, Lanz et al., (2010) investigated pyroclastic cones in Utopia Planitia, Mars, which interacted with water ice.

## 2.4 Impact Craters

Impact craters are found on every terrestrial planet in the solar system. Impact craters on Earth were formed in the presence of atmosphere and volatiles as were the impact craters on Mars so that studying impact craters on Earth helps understand impact craters on Mars. Impact craters are caused by high velocity impactor objects, including comets asteroids that collide with the surface of the planets and other objects in the solar system (Carr, 2006). The size of the impact crater depends on the mass and velocity of the impactor and the geology of the impacted surface (Carr, 2006).

Impact crater morphology can be described as simple, (e.g., Meteor Crater- Arizona, Endurance crater and Fram crater-Mars), and complex, (e.g., Gale crater- Mars) (Carr, 2006). Simple craters resemble a deep bowl with a diameter smaller than 4 kilometers (Carr, 2006). The bedrock at the top of the crater walls are layered horizontally and the talus slopes has a radial pattern which converges at the center of the crater. The ejecta blanket is continuous on the rim of the crater (Collins et al., 2012) (Figure 2.14).

Complex craters have a wider diameter bigger than 4 kilometers with a flat floor and central uplift (Carr, 2006). The walls are terraced, and the ejecta blanket is continuous (Collins et

al., 2012) (Figure 2.14). It is inferred that the wide diameter is determined by the mass and velocity of the impactor.

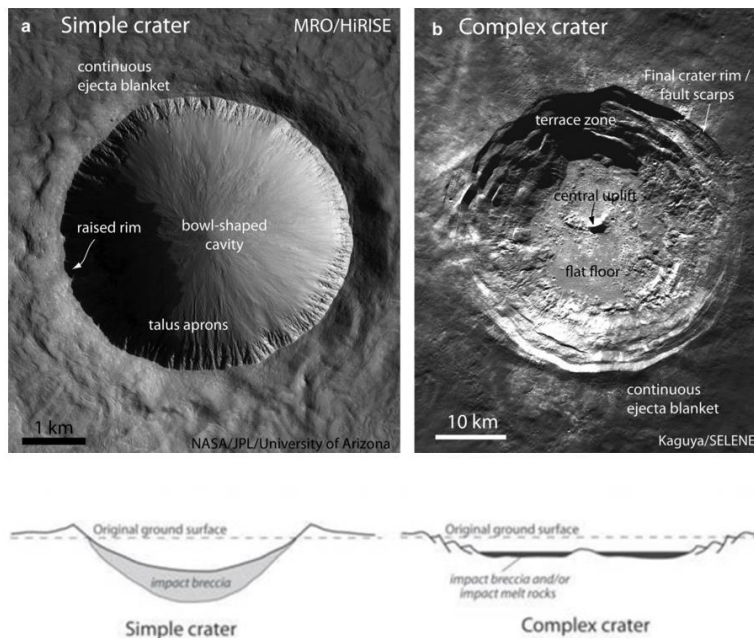


Figure 2.14. Image a) shows an aerial view of a simple crater. The cross section below shows the deep bowl shape of the crater. Image b) shows an aerial view of a complex crater on the moon with the peak in the middle and the terraces on the crater walls. The cross section below shows that the crater floor is shallow (Kaguya/SELENE image; Collins et al., 2012).

Impact craters have distinct features formed by the metamorphism of impacted rock due to the high pressure and temperature created with the release of the impactor's kinetic energy on impact. The rocks experience shock at the impact which produce metamorphosed rocks called impactites (Figure 2.15). These rocks are impact breccias; of lithic (clast-rich) to clast-poor rocks depending on the geology of the area (Collins et al., 2012). Shatter cones are formed due to tensional stresses produced by the shock waves of the rocks. These conical features are compared to the strands of horse hairs from millimeters to meters in length (Osinski & Ferrière, 2016) (Figure 2.16a). Impactites with a glass content of approximately 90% have been termed suevites (Masaitis, 1999) (Figure 2.16b). Another impact feature is pseudotachylite veins (Figure 2.17). These veins can be seen in the rocks of the central uplift, formed by friction within the



crater floor and below the crater during the shock compression phase of the impact (Kenkmann et al., 2014).

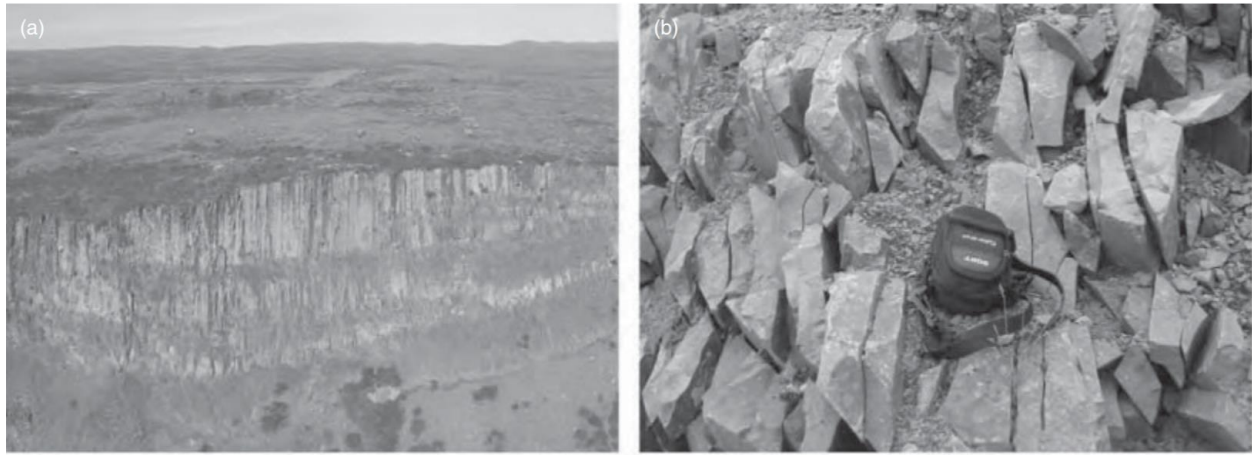


Figure 2.15. Image a) aerial view of the 80 m high cliffs of the Mistastin impact structure, Labrador, Canada. The white streaks in the middle of the image are the impact melts. Image b) fine grained impact melt rock from the Discovery Hill locality, Mistastin impact structure (Osinski et al., 2006).

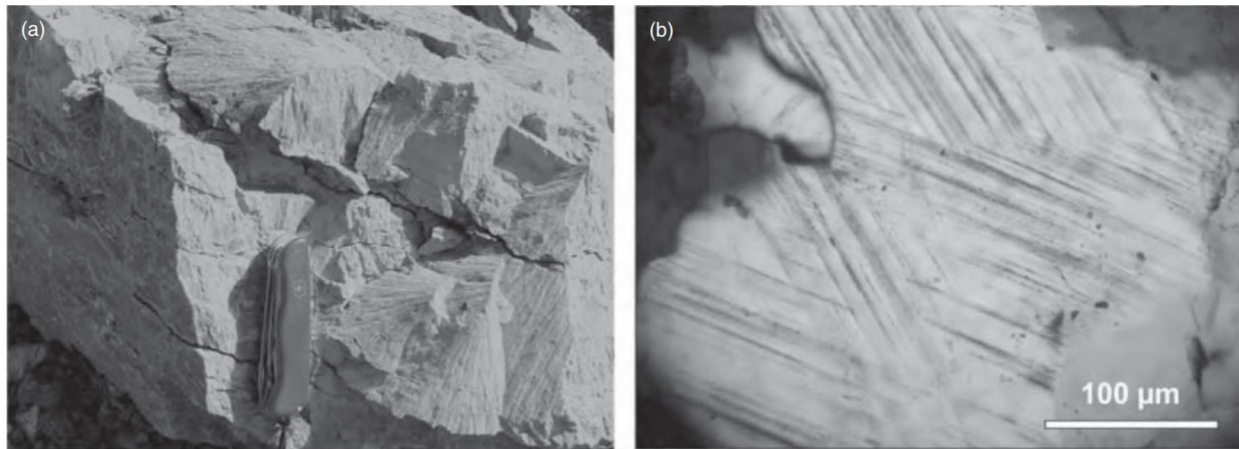


Figure 2.16. Image a) shatter cones (thin hair like strands) in limestone from the Houghton impact structure in Canada. Image b) microscopic planar deformation of the glass in the quartz (Osinski et al., 2006).



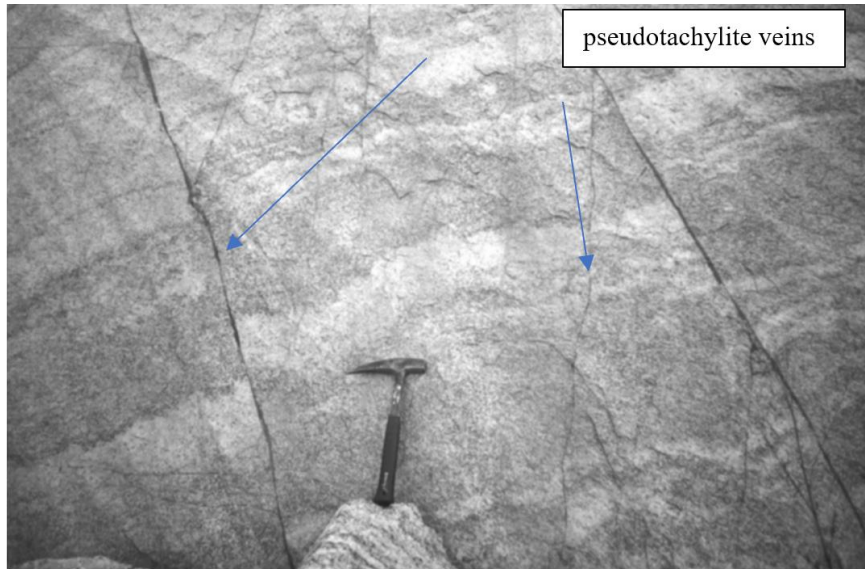


Figure 2.17. Image of pseudotachylite veins in a granitic rock Parys, South Africa. Rock hammer for scale (Melosh, 2005).

#### 2.4.1 Impact Crater Formation

The formation of impact craters occurs in a three-stage process: the contact/compression stage, the excavation stage and the modification stage. The three stages occur with both crater types, but the dynamics differ for excavation stage and the modification stage. Figure 2.18 are models of the formation of a simple crater and a complex crater.

The contact/compression stage begins when an impacting object such as an asteroid meets the surface of the planet and penetrates the land. The energy of the impactor is transformed into shock waves that propagate outward from the impact site. An explosive pocket of hot gas is produced from the high energy collision. The impact explosion usually produces a circular crater. In some cases, elliptical craters are formed when the impactor approaches at a low-angle or oblique to the surface (Carr, 2006) (Figure 2.18).

During the excavation stage, a transient crater is formed. In this stage, the land experiences compression. The contact of the impactor displaces the material on the surface of the land. The surface fragments and ejecta form an ejecta curtain that falls as an ejecta blanket

surrounding the crater (Carr, 2006). At the simple crater, the result of the transient crater is a deep bowl-shaped depression with minor melt flow at the crater rim. At the complex crater the crater floor experiences uplift as excavation continues and forms ballistic ejecta beyond the crater rim (Osinski et al., 2006) (Figure 2.18).

The modification stage begins after the formation of the transient crater. At the simple crater, minor melt flow begins to slump into the crater. At the complex crater, gravity causes the collapse of the crater walls causes the walls to be terraced and the central uplift on the crater floor is formed. Melt and clasts flow out of the central uplift where impactites are formed. The ratio of depth to diameter of complex crater is less than 1:5 (Collins et al., 2012) (Figure 2.18).

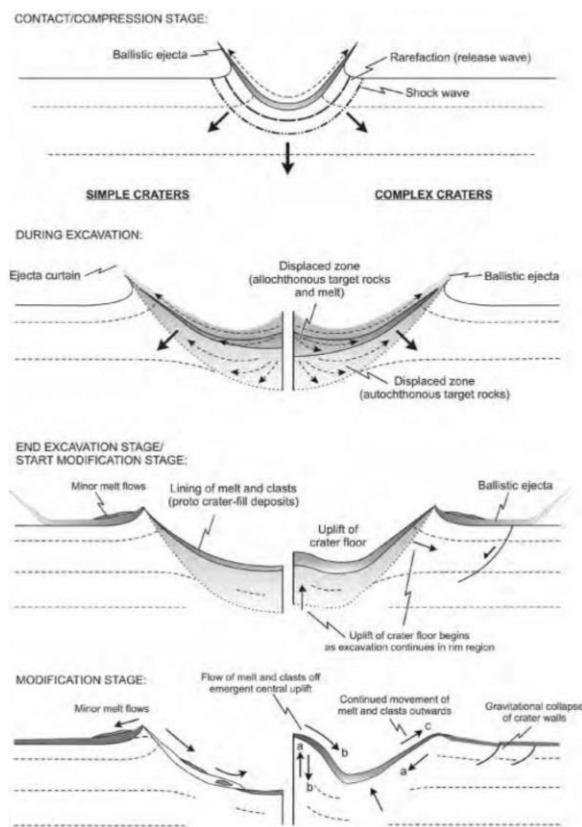


Figure 2.18. Cross-sectional model of crater formation. At the contact/compression stage the processes are the same for both crater type. At the exaction and modification stages, the processes are a bit different as the formed features are different (Osinski et al., 2006).

There are over 150 discovered impact craters on Earth, but weathering and erosion make them difficult to analyze. Scientists study impact craters through aerial imaging, satellite imaging, geomorphology, geophysics techniques of low gravity readings in the brecciation and fracturing of the rocks and low magmatic readings. An important advantage of impact cratering is that material from depth of the planet is brought to the surface in the form of ejecta deposits (Osinski & Pierazzo, 2013). The Ries crater in Germany and the Chicxulub crater in Mexico are two impact craters on Earth.

The Ries crater, Germany is 26 kilometers in diameter and formed 14.3 Ma (Kenkmann & Schöniel, 2006). The ejecta is composed of unshocked to weakly shocked breccia called the Bunte breccia. (Figure 2.19) illustrates the position of the 8 meters thick Bunte breccia sitting above the Malmian  $\delta$  limestones at Gundelsheim (GUN) (Kenkmann & Schöniel, 2006). There is a “detachment”- an area of weakness along a fault, 12 meters below the striated contact surface. The deposits of Bunte breccia is observed in the ejecta blanket, south and east of the crater and extend 3 crater radii from the crater center (Kenkmann & Schöniel, 2006). This significant impact crater on Earth aids in the study of processes of excavation and deformation. Areas where the target rocks are seen beneath contact with the ejecta blanket expresses the deformation features. The Bunte breccia extends to distances of 0.9 to 1.8 of the crater radii (Kenkmann & Schöniel, 2006).

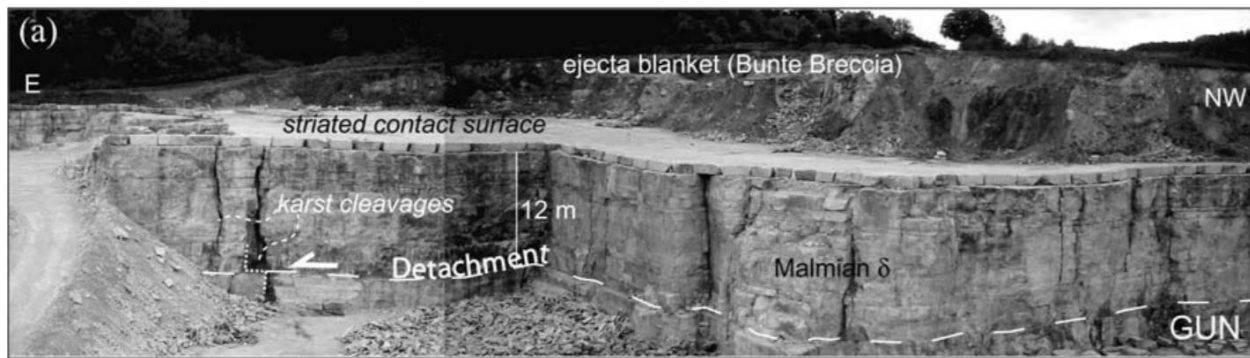


Figure 3.19 Image of Ries crater Germany showing the location and deposition of the ejecta blanket, the boundaries of the Malmian  $\delta$  limestones (Kenkmann & Schönián, 2006).

The Chicxulub crater in Mexico is approximately 12 kilometers below the Yucatan Peninsula. This buried structure is 180 kilometers in diameter and formed 65 Ma (Kenkmann & Schönián, 2006). Chicxulub crater was identified as the impact crater of the impact event that is thought to have taken place at the Cretaceous/ Tertiary (K/T) boundary that led to the mass extinction approximately 80% of all species including the dinosaurs. Sections of the ejecta blanket were discovered near the Albion Island quarry, in northwestern Belize, as quartz grains show effects of metamorphic shock. Also, the ejecta in the Rio Hondo region showed shocked crystalline basement clasts and altered melt particles. Upper Cretaceous rocks and Pre- (K/T) rocks beneath the ejecta blanket are karstified. These rocks are limestones, recognized by fractures and solution breccias near the Albion Islands. Petrographic and sedimentology data of the rock samples indicate that the crater is impact. The Chicxulub crater helped in the understanding of ejecta fluidization and analogous to rampart craters on Mars (Kenkmann & Schönián, 2006).

#### 2.4.2 Impact craters on Mars

Mars' impact craters are different from those of other planets because of the thin atmosphere and the presence of subsurface reservoirs of ice and liquids (Barlow, 2005). Mars

impact craters are better preserved than those on Earth because of the much less active weathering and erosion processes (Osinski & Pierazzo, 2013). Scientists understand the Martian surface by analyzing the particle sizes and the subsurface volatiles. Barlow, (2005) stated that about 25% of Martian impact craters have an ejecta blanket, the materials excavated due to the impact and thrown into the atmosphere, then settle in and around the craters. Images taken from THEMIS daytime IR (Figure 2.20) show a layer of ‘fluidized’ structure surrounding the crater greater than 4 km in diameter of ejecta. The fluidized structure resembles a flow moving outwards away from the crater (Barlow, 2005).

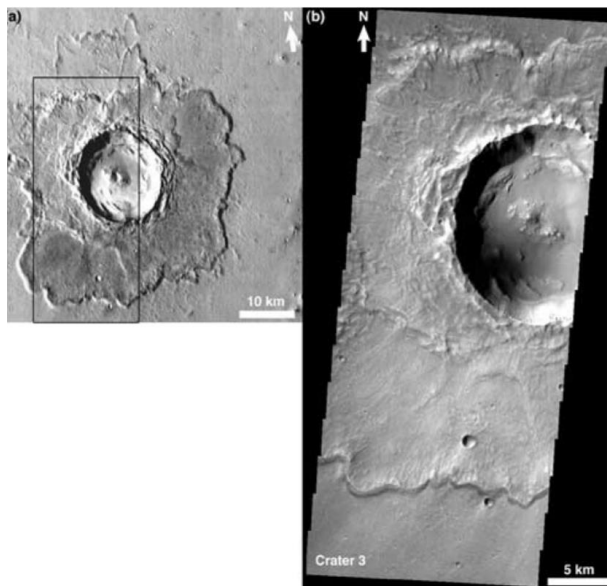


Figure 2.20. The image in a) shows a well-defined rampart crater and its flow pattern from the outer crater walls. The image was taken from THEMIS daytime IR images. The image in b) shows a close-up view of the fluidized flow pattern (Bologa et al., 2005).

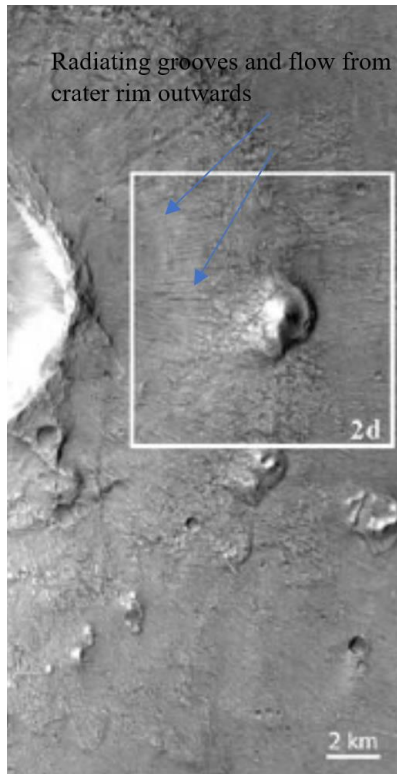


Figure 2.21. The image shows the radiating grooves and the direction of flow from the crater rim outwards. The blue arrows point out the lines which are the flow. The image was taken from THEMIS (Bologa et al., 2005).

Rampart craters are the most common type of impact crater found on Mars. This type of crater is unique to Mars, as there is an ejecta pattern and radiating grooves moving from the outer walls of the crater to the outer part of the Martian surface (Figure 2.21). The flow pattern surrounding the crater, suggests that the impactor melted the subsurface materials, which caused them to flow away from the impact point, then being solidified into a gently sloping wall at the end of the flow. Many scientists claim that the melted ejecta was caused by atmospheric gases in the ejecta and water from melted permafrost. The melted permafrost allowed the materials to flow away from the point of impact (Figure 2.20) (Bologa et al., 2005).

## 2.5 Identifying impact craters and maar craters

This thesis introduces students to a geologic problem and provide the techniques to solve them, they will appreciate the options as well as the limitations of using a rover to adequately

describe a remote location. The site used to collect data for the game, resemble holes in the ground as seen from orbit. The holes can be taken for a maar or an impact crater. By understanding the differences in physical features between a maar and an impact will the students be able to correctly identify the origin of the huge depressions in the ground.

Table 2-2 is a list of features students might use as a “checklist” when using the game, Hebebot: A Martian Expedition to a Terrestrial Analog to describe the remote location. Students will learn the characteristics and physical features of maar and impact craters through lessons prior to the game. Chapter 1 of this thesis provides the details of the information of each lesson.

**Table 2-2.** Features formed at Impact Craters and Maar Craters

<b>Categories</b>	<b>Impact Craters</b>	<b>Maar Craters</b>
<b>Floor</b>	simple crater- bowl shaped complex crater- usually flat or broad. Central peaks	bowled shaped/ funnel shaped
<b>Walls</b>	simple crater- smooth and steep complex crater- terraces due to slumping	steep walls, some areas may have parent rocks
<b>Rim</b>	elevated rim surrounding crater	Elevated rim- lapilli tuff
<b>Ejecta</b>	rock material deposited all around from the crater rim, thinning outwards, brecciated rocks	materials of rocks, ash, tuff of ash, ballistic trajectories, juvenile rocks with vesicles
<b>Rays</b>	bright streaks extending away from the crater	N/A
<b>Crater features</b>	impactites shatter cones pseudotachylite veins suevites	scoria piles tuff beds horizontal beds of ash on rim

## Chapter 3: Results from Ubehebe Volcanic Field Death Valley, California

### 3.1 Introduction

The Ubehebe Volcanic Field in Death Valley National Park, California provides an excellent opportunity to describe and document the geomorphologic features of a maar. The Ubehebe Volcanic Field is a unique feature of 12 maars (Crowe & Fisher, 1973) of which the Ubehebe Crater and Little Hebe are the best preserved. Ubehebe Crater is the largest, with a diameter of 700–800 meters and a depth of 235 meters (Crowe & Fisher, 1973). These maars were formed after magma rose through the feeder dyke and interacted explosively with groundwater. The interaction of the magma and groundwater caused the erupted material to become brittle so that the thermohydraulic explosion caused the surrounding country rocks to be fragmented (Lorenez, 2003). The rocks within the craters are of different chemical compositions and physical appearances with igneous and sedimentary rocks occurring side by side within the craters and along their tephra.

The evidence of the phreatomagmatic eruptions includes; the fragmented black basaltic rocks that cover the surroundings of the craters, the layers of ash on the tephra rims, scoria piles on the crater walls, the silt and sand at the bottom of the crater, and quartz- clasts amongst the vesicular mafic rocks (Fierstein, 2017).

Protruding from the walls of the Ubehebe Crater is a red-brown and yellow conglomerate of Miocene age (Snow & Lux, 1999). A band of Paleozoic carbonate rocks that underlies the Cottonwood Mountain became deformed by thrusting and folding from the Permian to Cretaceous (Sasnett et al., 2012). These carbonate rocks project beneath the Miocene rocks near Ubehebe Crater. Within the craters and the surrounding area, there are samples of the accidentals



and juvenile rocks in plain sight. Analyzing these rocks provides a basis for determining the nature of the eruptions.

The rock samples collected at Ubehebe Volcanic Field provide the data used in the development of the game application, Hebebot: A Martian Expedition to a Terrestrial Analog. The goal of this chapter is to describe the field results which were used as data for the game and, to put the samples into their regional context. The game is designed to mimic the processes and procedures of a Martian rover, from following its traverse to collecting and analyzing rock samples. The photographic, petrographic and geochemical data described in this chapter are the information used to develop the game. The panoramas taken during field work provide the visual images of the sites that the player investigates, as he/she looks for geomorphological evidence of the origin of the crater. Mars Hand Lens Imager (MAHLI) images will show the micro images of the rocks and the petrographic and geochemical data are additional data that describe the geology of the area. Combined, this data determines the end results of the game.

Information of previous Martian missions was gathered from orbital images and the instruments on the landers. Further great discoveries were made possible from information retrieved by the rovers. The operation of the Martian rovers relies on orbital images, panoramic images, microscopic images, MAHLI images and rock analysis to provide a basis for the interpretation of the geologic history of a region of Mars. The rovers are equipped with instruments that analyze the collected rock samples while on their traverses on the Martian surface. The Mars Exploration Rovers (MER) Spirit and Opportunity have analyzed Martian basaltic rocks and sediments with an instrument called the Alpha- Particle X-ray Spectrometer (APXS) (Campbell et al., 2011). The Mars Science Laboratory (MSL) Curiosity has also used APXS (Grotzinger et al., 2012). This APXS is mounted on the rover and measures the chemical

composition of rocks and soils using X-ray spectroscopy and X-ray Fluorescence (XRF) (Gellert et al., 2015). XRF was used to collect geochemical data from the samples collected at the Ubehebe sites and that information is used in the game application. Collectively, the images of large-scale features in the craters, micro-images MAHLI, petrographic images and the XRF results of the rock samples collected from the field and included in the game provide the basis for the player to determine whether the craters were created by volcanic eruptions or by impacting objects on the Martian surface.

Field work data was collected at an alluvial fan in Death Valley. The information is in Appendix A. The data will be used for future game development.

## 3.2 Methods

Several methods were used to unravel the morphology and geology of the Ubehebe Volcanic Field. This section describes the methods employed, first those methods that were used in the field, followed by laboratory methods that were used to analyze samples that were collected during field work.

### 3.2.1 Field methods

Data was collected in the form of high-resolution images of the morphology of Ubehebe Crater, Little Hebe, and an alluvial fan. A Nikon camera was programmed with the GigaPan EPIC Pro. The GigaPan EPIC Pro is an instrument programmed with a camera to take a series of pictures of a scene (GigaPan Systems, 2013). The GigaPan EPIC Pro was used to capture stunning panoramic gigapixel images by “stitching” 52 to 192 pictures in each infinite panorama. Infinite panoramas capture the scenery of the landform feature. Near field panoramas were smaller, within the range of 54 to 96 images. A near field panorama captures an image of the ground below the gigapan and camera mount. MAHLI images of individual rock samples were

also captured by the camera. By mimicking a Martian rover's traverse, five stops were recorded as sites at Ubehebe Crater and Little Hebe. A Global Positioning System (GPS) was used to give coordinates of the exact location of each site. The MAHLI-scale images that were taken of rock samples in the field were described in terms of their physical features and textures. A centimeter scale was placed next to the rock samples on the ground, while in their original (*in situ*) position before the rock samples were collected in labelled sample bags. The pictures were uploaded on a laptop. PTGui stitching software was used to stitch photographs into panoramic images and near field images (PTGui., 2000-2019).

### 3.2.2 Petrographic methods

Petrographic thin sections were prepared by Martin Ouellette at the Brock University Petrographic Laboratory. Five rock samples from the Ubehebe Volcanic Field were processed using standard petrographic techniques. The mineralogy of the rocks was determined using an Olympus BX51 microscope. The images of the minerals were captured using the cellSens Standards software. The cellSens Standard software conducts microscopic analysis on microscopic images (cellSens Standard, 2019). The microscopic images were collected through Crossed Polarized Light (XPL) at magnifications 5x.

### 3.2.3 X-ray Fluorescence methods

At Brock University, six samples were crushed in the Petrographic Laboratory, labeled and shipped to Hamilton Analytical Lab, Hamilton College, for XRF processing. XRF is a technique used to provide an elemental analysis of the rock samples. This process uses high energy x-rays to excite the atomic structure of the rock elements. This process allows a single low dilution fusion (2:1 ratio) of Li-tetraborate fused bead to provide accurate data of the major elements in the rocks (Johnson et al. 1999). XRF provided major element concentrations

expressed as oxide weight percentages each > 0.1 % and include SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, FeO, MnO, MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, and P<sub>2</sub>O<sub>5</sub>. Trace elements including Cr and Ni were provided.

### 3.3 Field Results

#### 3.3.1 Ubehebe Volcanic Field craters image results

Figure 3.1 shows an aerial image of the field site where the data was collected, the five sites mapped in with the GPS coordinates. Table 3-1 provides GPS coordinates for the 5 sites that were photographed and/or sampled and a description of each site. Table 3-2 describes the rocks that were collected at each site. Figure 3.2 includes images of the features and volcanic deposits within the Ubehebe Crater. In Figure 3.2, A shows sandstone blocks jutting out of the north wall. B shows the red- orange colored bedrock, and small alluvial fans at the lower portion of the crater. C shows another sandstone block protruding from the walls of the crater. Tephra rings are depositional features made up of ash and scoria piles, which fall on the crater rims after a phreatomagmatic eruption. D shows scoria piles near the rim of the crater. The slope of the rim, into the crater, is ~30°. E shows a fault line separating the yellow sediments on the left and the orange sediments on the right. F shows the layered tephra rim of ash. Figure 3.3 shows three rocks that were collected at the bottom of the Ubehebe crater. A show a vesicular black rock next to a coarse grained sandstone rock. B shows an orange rock lodged into the clast supported bedded tuff. C shows a coarse-grained sandstone.

Maar craters are surrounded by low-profile tephra rings of pyroclastic deposits of massive tuff breccias, bedded and cross-bedded tuffs and lapilli tuffs. Tuff beds are seen on the tephra rim of Little Hebe (Valentine et al., 2017). Figure 3.4 shows images of Little Hebe. A shows pyroclastic deposits on the crater rim/ tuff and ash deposits. B shows an approximately 1-meter

high vertical surface exposing tuff. C is an image of the slope of the outer surface of the raised crater rim sloping downward to the land surface that surrounds the crater.

Figure 3.5 shows the images collected at Site 1. Image A is a 180° panorama of the land surface adjacent to Little Hebe crater on the right and shows the location where samples were collected. Image B shows a 180° near field panorama of the collected rocks in their original position. The mixture of different rock fragments is seen in this image, the fragmented rock pieces fell back to the ground after being ejected from the eruption. The rocks range from black, brown, white and pink in colour and are a combination of sedimentary and igneous rocks. B i) and ii) are the MAHLI images of the rocks, descriptions in (Table 3-2).

Figure 3.6 shows the images collected at Site 2. Image A shows a 180° panorama of Little Hebe crater looking south. Image B shows a 180° near field panorama of the collected rocks in their original position. The mixture of different rock fragments is seen in this image; the fragmented rock pieces fell back to the ground after being ejected from the eruption. The rocks range from black, brown, white and pink in colour and are a combination of sedimentary and igneous rocks. B i) and ii) (x and y) are the MAHLI images of the rocks, descriptions in (Table 3-2).

Figure 3.7 shows the images collected at Site 3. Image A shows a 180° panorama of Little Hebe crater looking west. Image B shows a 180° near field panorama of the collected rock in its original position. The mixture of different rock fragments is seen in this image, the fragmented rock pieces fell back to the ground after being ejected from the eruption. The rocks range from black, brown, white and pink in colour and are a combination of sedimentary and igneous rocks. B i) is the MAHLI images of the rock, descriptions in (Table 3-2).

Figure 3.8. shows the image collected at Site 4, the 180° panorama image of Ubehebe Crater from the west. Image showing exposed bedrocks, alluvial fans at the lower section of the crater, and the black fragmented mafic rocks which drapes the crater rim.

Figure 3.9 shows the image collected for Site 4, the 360° panorama image of Ubehebe Crater from the bottom. The 360° image is flattened to fit the page, therefore the sandstone rock can be seen jutting out of the crater wall in the north, the exposed sandstone bedrocks are seen in the east. The images collected at the different sites, illustrate the environmental features created after a phreatomagmatic eruption. These specific eruptions formed a maar volcanic field.

**Table 4-1. GPS locations, compass bearings and descriptions of each location**

<b>Site 1- Approach to Little Hebe</b>	
GPS Location	N 37°00.4515', W117°451.106'
Compass Bearings: Infinite panorama Nearfield panorama	30°- 270° 180°- 305°
Description of Location	Approach of Little Hebe from the east. The ridge is made of buff and black bedded tuff. 180° panorama showing the view to the south (Figure 3.5 A).
<b>Site 2-North west rim of Little Hebe</b>	
GPS Location	N 37°00.4555', W 117°45.2006'
Compass Bearings Infinite panorama Nearfield panorama	125°- 240° 180°- 210°
Description of Location	Northwest rim of Little Hebe. 180°panorama of Little Hebe, parts of the rim is in full sun illuminating the western side, red/black tuff beds (Figure 3.6A).
<b>Site 3- West Rim of Little Hebe</b>	
GPS Location	N 37°00.3915', W 117°45.1704'
Compass Bearings Infinite panorama Nearfield panorama	80°- 350° 180°-210°
Description of Location	West rim of Little Hebe. 180° panorama showing the tuff beds on the rim of the crater (Figure 3.7A).
<b>Site 4- East view of Ubehebe Crater</b>	
GPS Location	N 37°01.11115', W 117°45.4706'
Compass Bearing Infinite panorama	35°-135°
Description of Location	West parking lot side of Ubehebe Crater. View is from a position on the western side of the crater, looking over the crater. 180°panorama view of the rim of the crater (Figure 3.8).
<b>Site 5- 360° at the bottom of Ubehebe Crater</b>	
GPS Location	N 37°01.0015', W 117°45.0706'
Compass Bearing Infinite panorama	0°-360°
Description of Location	Panorama 360° from the bottom of the Ubehebe Crater. Red and orange bedded units exposed at the base of the Northeast wall of Ubehebe. They are made up of interbedded sandstone and conglomerate (Figure 3.9).

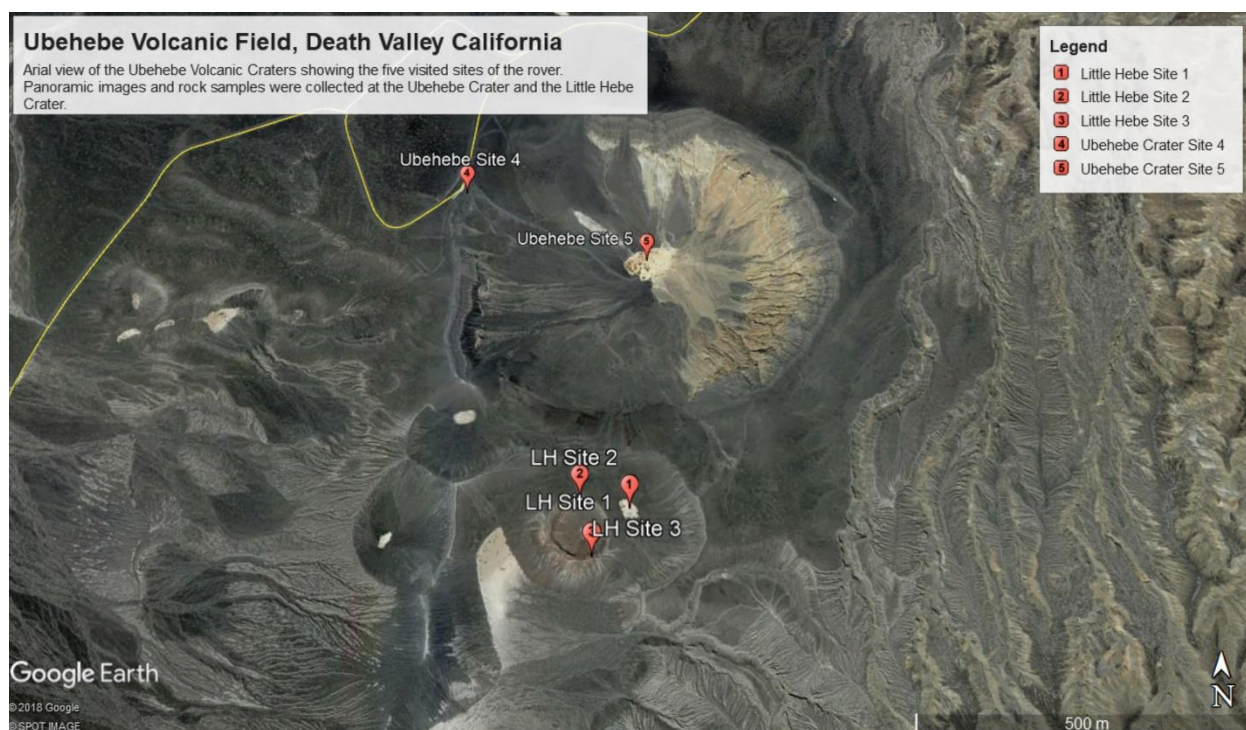


Figure 3.1. Aerial view of the 5 sites. Three sites are of Little Hebe and two sites are of Ubehebe Crater (GoogleEarth, 2013).

**Table 3-2.** The rock samples with their descriptions used in the game, collected at Ubehebe Volcanic Field Sites, Death Valley California

Sample number	Rocks descriptions	Rock Image
<b>Site 1</b>		
1-17-3	0.06 - 2mm fine grained, smooth, grey accidental	Figure 3.5B ii)
1-17-1	aphanitic vesicular black mafic, 1 cm quartzite xenolith scoria	Figure 3.5B i)
<b>Site 2</b>		
2-17-1A	0.06 - 2mm fine grained, gritty to touch, sub-angular white sandstone	Figure 3.6B ii-x)
2-17-1B	aphanitic vesicular black mafic, scoria	Figure 3.6B ii-y)
2-17-2	0.2-0.6mm medium grained, granulated, >90% quartz, pink quartzite	Figure 3.6B i)
<b>Site 3</b>		
3-17-1	0.06 - 2mm fine grained, greywacke accidental	Figure 3.6B i)



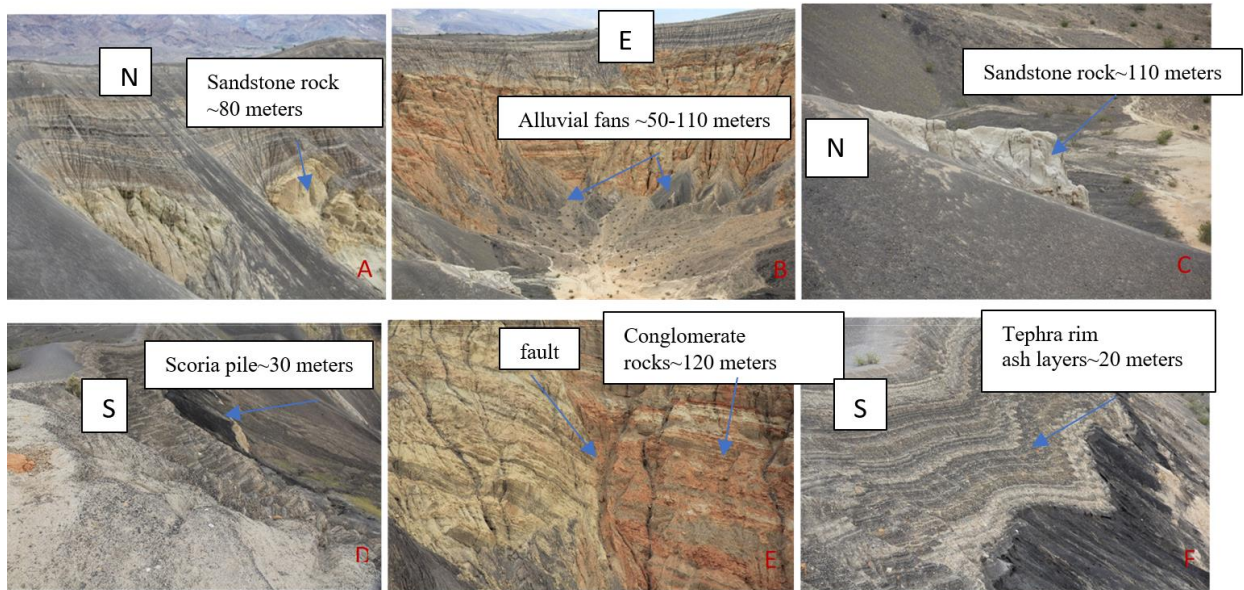


Figure 3.2. Ubehebe Crater images. A: Sandstone rock protruding through the north wall~. B: Reddish orange-colored conglomerate makes up the exposed bedrock, small alluvial fans seen at the lower portion of the crater. C: Sandstone protruding from the walls of the crater. D: Steep sides of the crater with scoria pile. E: on the left these sediments are yellow and, on the right, they are orange, this is due to a fault that separates the two different sedimentary units. F: Layered tephra rim at the top. Letters N, E and S correspond to north, east and south compass directions.



Figure 3.3. Images of rocks at the bottom of the Ubehebe Crater. Image A showing an igneous rock near a sedimentary rock. Image B showing a sedimentary rock (bomb sag) logged in the crater wall. Image C showing a coarse-grained sedimentary rock.

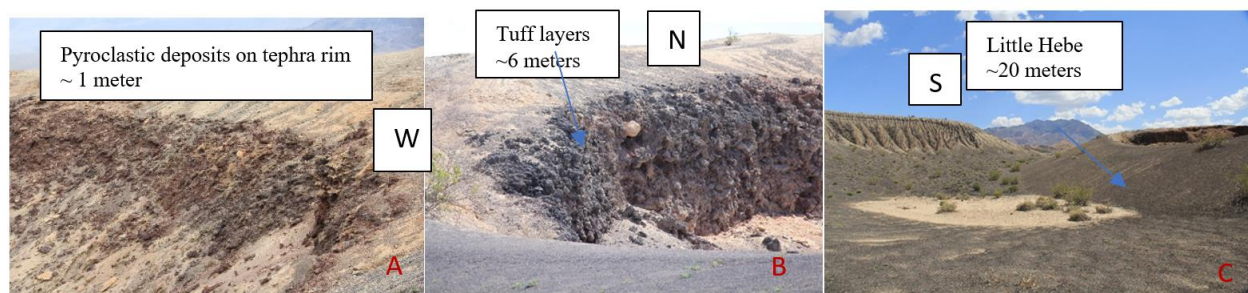


Figure 3.4. Little Hebe crater images. Image A showing pyroclastic deposits on the tephra rim west of crater rim. Image B showing tuff layers north of the crater. Image C showing longitudinal view of the crater right side of image.

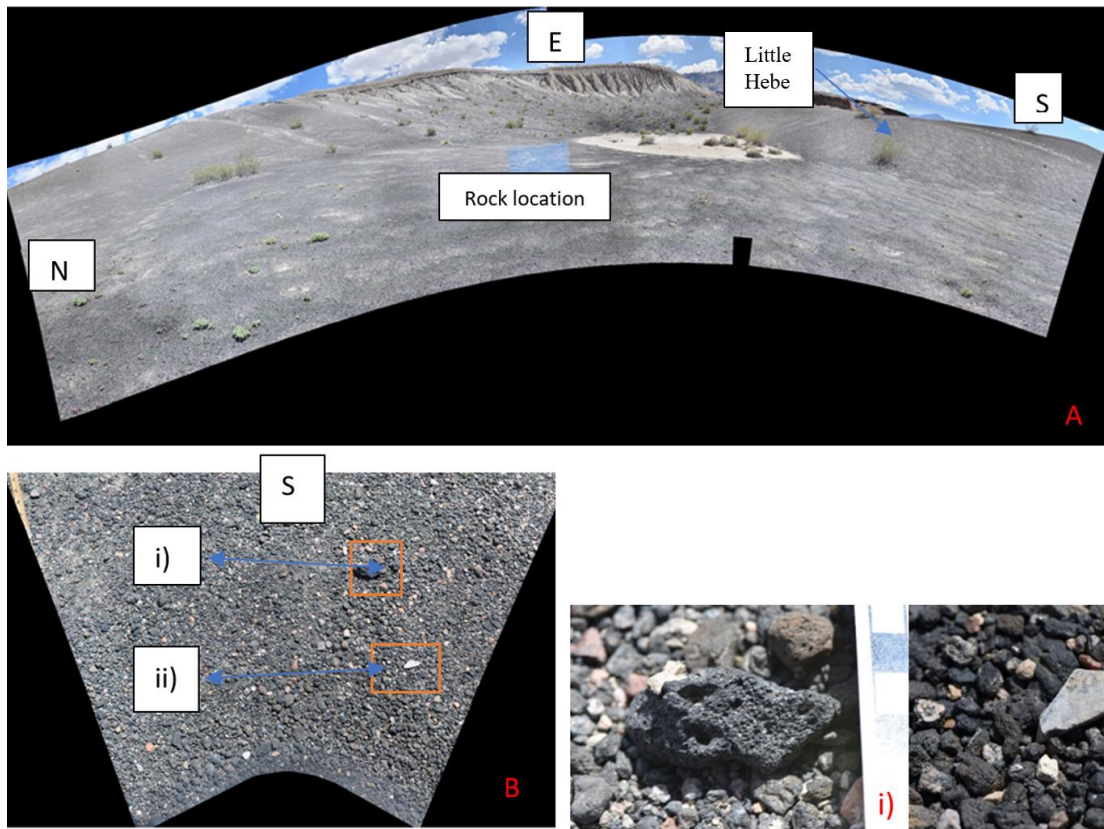


Figure 3.5. Site 1: Image A showing a 180° panorama of Little Hebe on the right side of the image and the location of the samples collected. Image B showing a 180° near field panorama of the collected rocks in their original position: Images i) and ii) are MAHLI-scale. Letters N, E, S and W correspond to north, east, south and west compass directions.



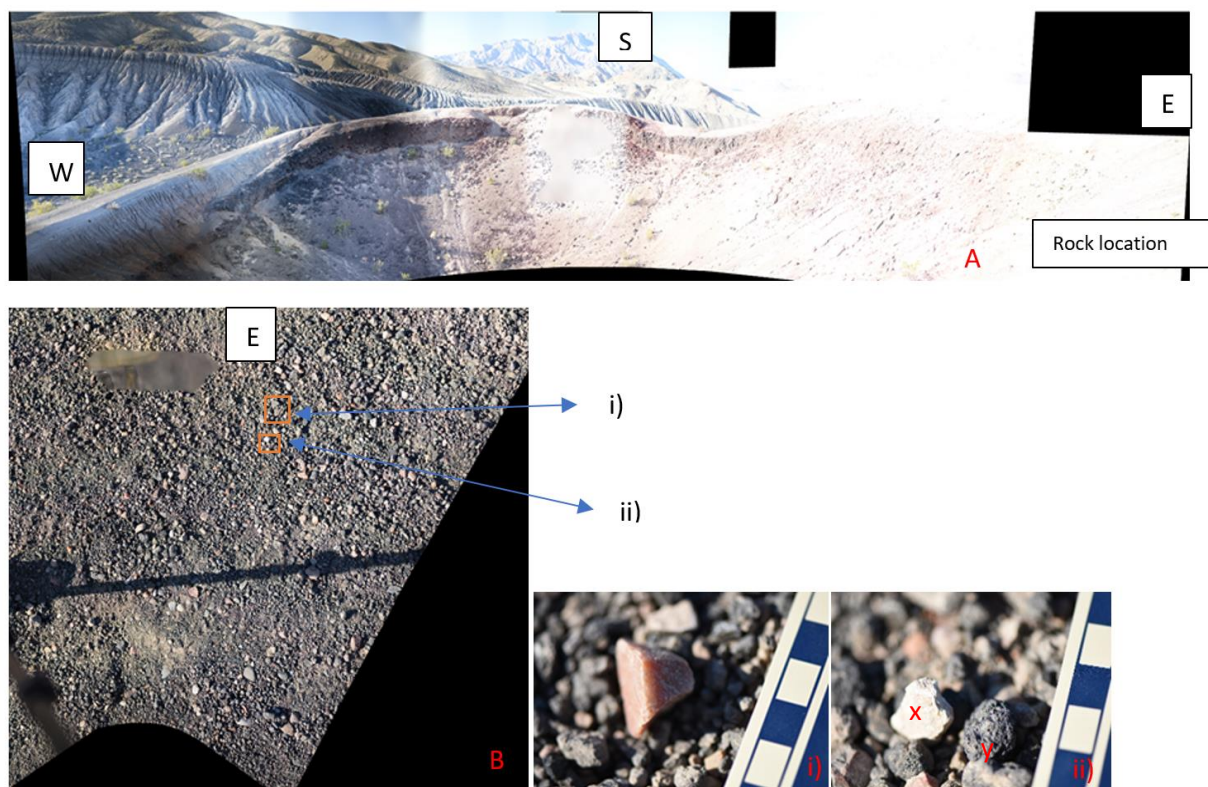


Figure 3.6. Site 2: Image A showing a 180° panorama of Little Hebe crater looking south. Image B showing a 180° near field panorama of the collected rocks in their original position. Images i) and ii) are MAHLI scale. Letters N, E, S and W correspond to north, east, south and west compass directions.

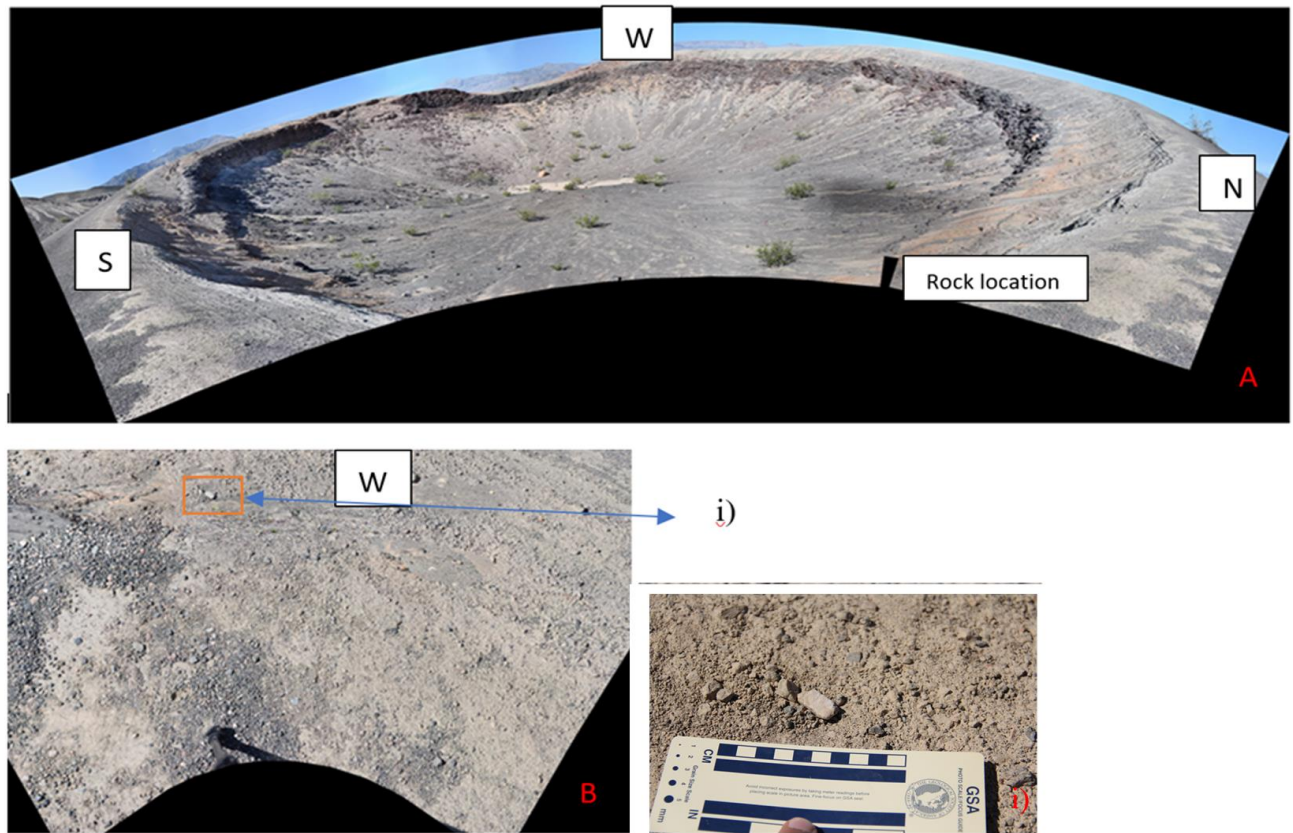


Figure 3.7. Site 3: Image A showing a 180° panorama of Little Hebe crater looking west. Image B showing a 180° near field panorama of the collected rocks in their original position. Image i) is MAHLI scale. Letters N, E, S and W correspond to north, east, south and west compass directions.

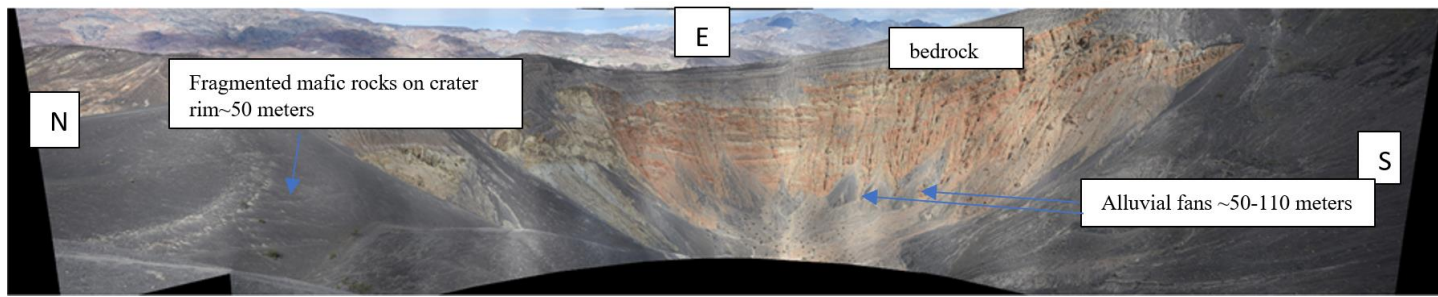


Figure 3.8. Site 4: 180° Panorama image of Ubehebe Crater from the west. Image showing exposed bedrocks, alluvial fans and crater rim. Letters N, E, S and W correspond to north, east, south and west compass directions.



Figure 3.9. 360° Panorama image of Ubehebe Crater from the bottom. The 360° image is flattened to fit the page, therefore the sandstone rock can be seen jutting out of the crater wall in the north, the exposed sandstone bedrocks are seen in the east. Letters N, E, S and W correspond to north, east, south and west compass directions.

### 3.3.2 Petrographic results

The Petrographic image of sample 5-17-1 contains feldspar phenocrysts example olivine, and plagioclase microlith in a groundmass of plagioclase, with rounded vesicles (Figure 3.10).

The petrographic image of sample 3-17-2 contains plagioclase phenocrysts, hornblende phenocrysts and subangular quartz grains (Figure 3.11). The petrographic image of sample 3-17-1 contains sharp angular quartz grains, and olivine in a calcareous cement. Volcanic clasts are amongst the quartz grains. The petrographic image of sample 1-17-2 contains > 90% rounded quartz grains and a few opaque grains, probably quartz in extinction in silica cement. The petrographic image of sample 1-17-1 contains an abundance of plagioclase microliths and a few feldspar phenocrysts, surrounded by small vesicles.

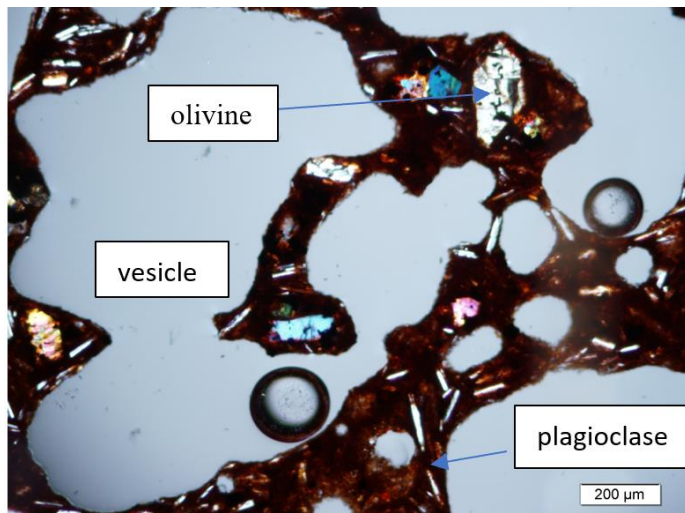


Figure 3.10. Photomicrograph of vesicular volcanic rock.  
Feldspar and plagioclase microlith in a groundmass of plagioclase. Crossed Polarized light, X5. Sample 5-17-1.



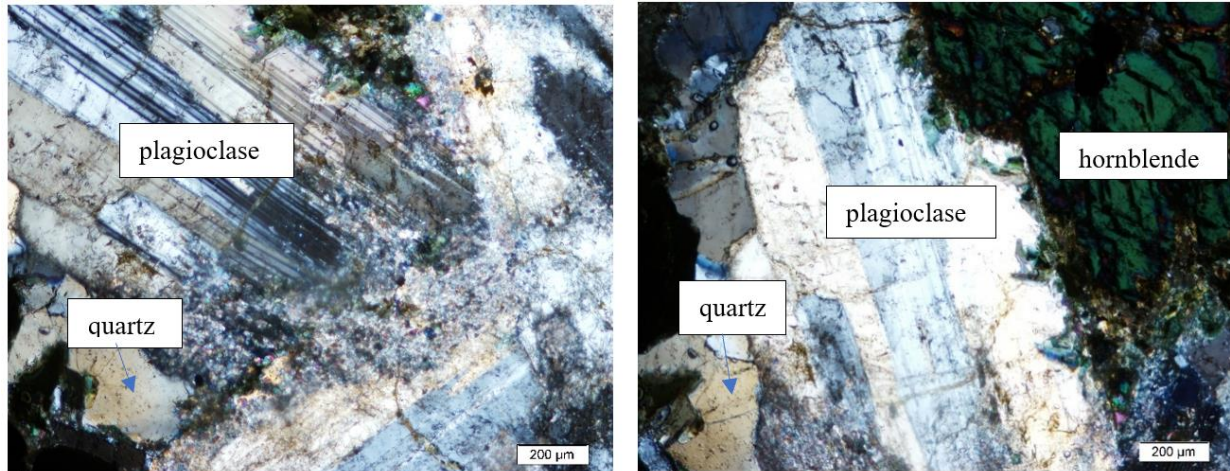


Figure 3.11. Photomicrograph of an igneous rock; plagioclase phenocryst, sub-angular quartz, hornblende phenocryst. Cross Polarized light, X5. Sample 3-17-2.

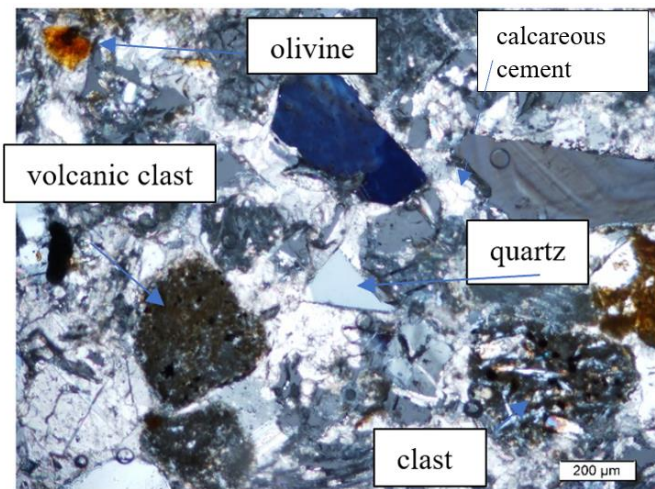


Figure 3.12. Photomicrograph of sandstone rock; sharp angled quartz grain, altered volcanic clast, olivine, microlithic clast fused with calcareous cement. Cross Polarized light, X5. Sample 3-17-1.

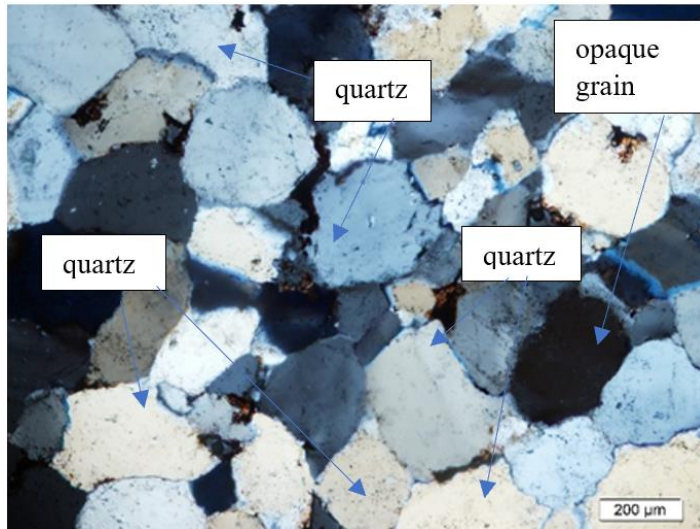


Figure 3.13. Photomicrograph of a sandstone; quartz grains are rounded and fused with silica cement. Crossed Polarized light, X5. Sample 1-17-2.

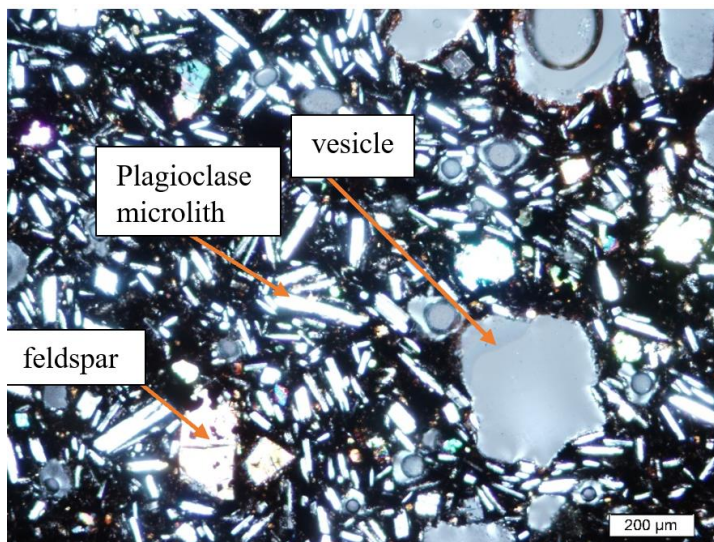


Figure 3.14. Photomicrograph of a vesicular volcanic rock, feldspar surrounded by plagioclase microlith. Crossed Polarized light, X5. Sample 1-17-1.



### 3.3.3 X-ray Florescence (XRF) rock sample results

XRF elemental compositions for the 6 rock samples from the Ubehebe and Little Hebe craters are presented in Table 3-4 and Table 3-5. Table 3-4 present the major elements weight percent oxides of  $\text{SiO}_2$ ,  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MnO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and  $\text{P}_2\text{O}_5$ . Table 3-5 present the trace elements of Ni, and Cr.

Elemental variation diagrams (Figure 3.15) demonstrate differences between the igneous elemental components for the six rock samples identified through XRF analysis, which help determine the rocks' types.

The Total Alkali-Silica (TAS) diagram (Le Bas, et al., 1985) is used to classify three of the Ubehebe craters rock samples (Figure 3.16). Table 3-6 classifies samples 5-17-1 and 1-17-1 as trachy-basalt and 3-17-2 as trachy-andesite. The other samples are included on the table, but they are of sedimentary lithologies.

**Table 3-3.** XRF Results of major elements, Hamilton Analytical Laboratory

Major Elements (wt.% oxide)	1-17-1	1-17-3	2-17-1	3-17-1	3-17-2	5-17-1
<b>SiO<sub>2</sub></b>	50.16	9.19	96.81	36.30	58.31	49.67
<b>TiO<sub>2</sub></b>	1.82	0.08	0.04	0.11	0.79	1.86
<b>Al<sub>2</sub>O<sub>3</sub></b>	16.18	1.03	0.15	7.09	17.17	16.49
<b>FeO</b>	9.47	0.54	0.34	0.65	6.37	9.53
<b>MnO</b>	0.17	0.02	0.01	2.25	0.25	0.17
<b>MgO</b>	5.08	18.28	0.26	0.93	0.93	5.04
<b>CaO</b>	7.93	28.15	0.78	27.37	27.37	7.89
<b>Na<sub>2</sub>O</b>	3.62	0.05	0.61	1.70	1.70	3.91
<b>K<sub>2</sub>O</b>	2.39	0.61	0.04	1.14	1.14	2.36
<b>P<sub>2</sub>O<sub>5</sub></b>	1.07	0.02	0.04	0.10	0.06	1.14

**Table 3-4.** XRF Results of trace elements, Hamilton Analytical Laboratory

Trace Elements (ppm)	1-17-1	1-17-3	2-17-1	3-17-1	3-17-2	5-17-1
<b>Ni</b>	49	6	3	6	20	55
<b>Cr</b>	77	16	28	14	31	83

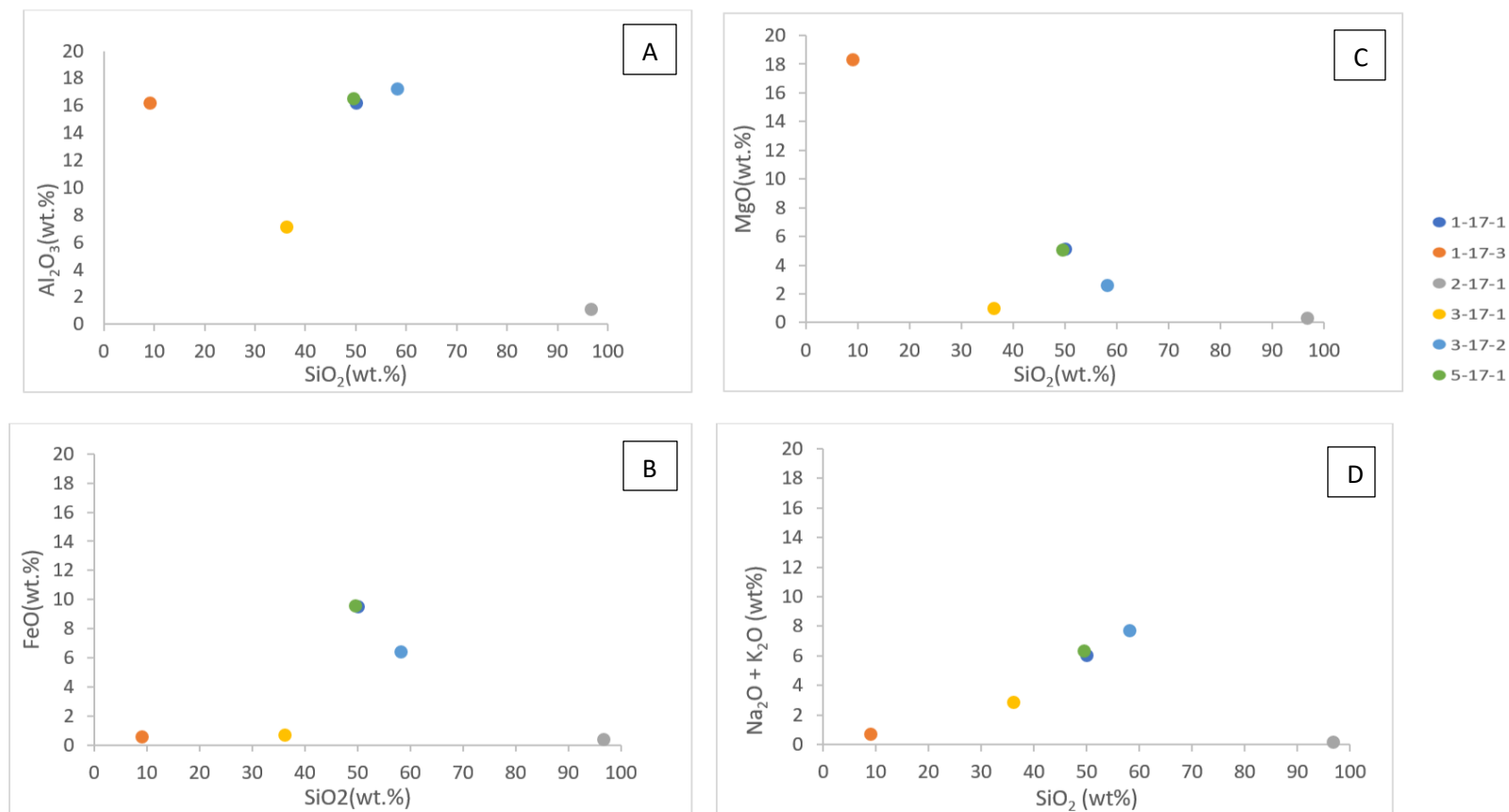


Figure 3.15.  $\text{SiO}_2$  elemental variation diagrams for the six rock samples collected at the Ubehebe Volcanic craters identified through XRF analysis. The weight percentages of the major elements' oxides are plotted. A)  $\text{Al}_2\text{O}_3$  vs  $\text{SiO}_2$ ; B)  $\text{FeO}$  vs  $\text{SiO}_2$ ; C)  $\text{MgO}$  vs  $\text{SiO}_2$ ; D)  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  vs  $\text{SiO}_2$

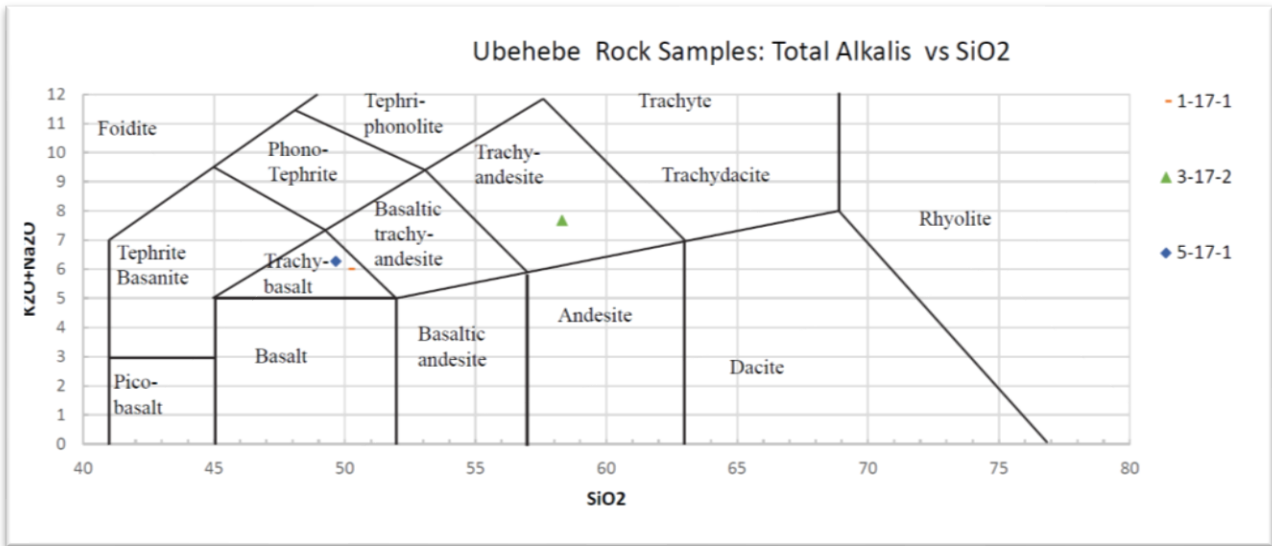


Figure 3.16. Total Alkali vs. Silica diagram for the chemical classification of igneous rocks (Le Bas et al.,1986). Sample 3-17-2 is in the Trachyandesite class, samples 5-17-1 and 1-17-1 are in the Trachy-basalt class.

**Table 3-5.** XRF-Data Results and Alkali ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ ) vs  $\text{SiO}_2$

Samples	Alkali vs $\text{SiO}_2$ plots	Possible Rock Classification
5-17-1	6-6.5 wt.% of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 40-60 wt. % of $\text{SiO}_2$	trachy-basalt
1-17-1	6-6.5 wt.% of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 40-60 wt. % of $\text{SiO}_2$	trachy- basalt
3-17-2	7wt%. of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 40-60 wt. % of $\text{SiO}_2$	trachy- andesite
3-17-1	2-3 wt.% of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 30-40 % of $\text{SiO}_2$	carbonate
2-17-1	<0.5 wt.% of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 96.81 wt.% $\text{SiO}_2$	sandstone
1-17-3	<1 wt.% of $\text{Na}_2\text{O}+\text{K}_2\text{O}$ 9.19 wt.% of $\text{SiO}_2$	mudstone

Sedimentary  
lithologies

### 3.4 Discussion

The panoramas and MAHLI images taken of the volcanic craters at Ubehebe Volcanic Field indicate a hydrovolcanic setting. The eruptions were phreatomagmatic (magma and water interaction), which formed maars. The physical features and depositional environment narrate the geologic past of the volcanic site.

The photographic data taken at the five field sites aligns with the geologic literature of the area. Snow & Wernicke, (2000) stated that the maars were created by phreatomagmatic eruptions which ejected both fragmental basalt, silt, sand, and larger clasts (>10 cm) from the Navadu Formation. The panoramas show the mafic volcanic rocks draped in and out of the craters (Figure 3.8). The Ubehebe Crater exposes the scoria piles within the walls of the crater and the bedrock made up of white/orange sedimentary rocks (Figure 3.2). The interaction of water and magma created an explosive eruption that caused the rocks to become fragmented. The near field panoramas illustrate the sandstone fragments amidst the mafic fragments, the clay fragments and quartzite rocks (Figure 3.5, 3.6, 3.7). The MAHLI images show the vesicles in the basalts which indicate degassing of the rocks (Figure 3.6, 3.5). The juvenile clasts are fine-grained fragmentation caused by magma–water interaction (Cagnoli, & Russell, 2000). The juvenile clasts are fine-grained because the magma cooled quickly. Tuff is a depositional feature of maar volcanoes, created pyroclastic burst of materials of ash and ash which form the tephra ring. Tuff of recent explosions are nonindurated. The panorama and individual images of the Little Hebe crater shows the tuff beds on the tephra rim and, the loose sediments detached from the original bed (Figure 3.4).

The minerals identified in the petrographic images supports the rocks compositions found at a maar. The petrographic slide shows the geology and the phreatomagmatic explosion of the

area. The tuff is composed of materials derived from ash and pyroclasts. In Figure 3.10, the sample contains vesicles and plagioclase in a plagioclase groundmass. The vesicles suggest escaped gases in the erupted material. The petrographic image contains phenocrysts of plagioclase and hornblende, minerals typical of igneous rocks (Figure 3.11).

The explosion of the Ubehebe Crater expelled accidentals of the sandstone bedrock and Paleozoic carbonate rocks beyond its crater. The petrographic image contains altered volcanic clasts, angular quartz grains and olivine in a calcareous cement (Figure 3.12). The petrographic image contains an abundance of quartz (Figure 3.13). The origin of the sandstones is from the sandstone and conglomerate basement rocks of the Ubehebe crater. The volcanic clasts in the petrographic image of the sandstone suggests that the phreatomagmatic explosion allowed both juvenile and accidental materials to be in contact.

The XRF analysis intended to help identify the igneous rocks by looking at the weight percentages of the oxides of the major elements present, and the trace elements (ppm) of each rock sample. Turekian (1963) suggested that levels of Cr and Ni indicate mafic igneous setting, because of the crystallization of minerals at high pressure and temperature during an explosive eruption. Table 3-4 show that the levels of Cr and Ni are high in the igneous rocks compared to the sedimentary rocks. Figure 3.16 plots the Total Alkali vs. Silica (TAS) diagram for the chemical classification of igneous rocks (Le Bas et al., 1986). The TAS diagram points out that the igneous samples are basalts. Samples 5-17-1- and 1-17-1 fall within 6-6.5 wt.% of  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  and 40-60 wt. % of  $\text{SiO}_2$  labelled as trachy-basalt and sample 3-17-2 falls within the 7wt%. of  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  and 40-60 wt.% of  $\text{SiO}_2$  as a trachy-andesite. Calzia, (2016) suggests that research has identified some of the basalts at the Ubehebe craters as trachy-basalts.

The SiO<sub>2</sub> elemental variations of the oxides Al<sub>2</sub>O<sub>3</sub>, FeO, MgO suggest that the erupted deposits comprise of conglomerate, sandstone, and/or lacustrine rocks, that came from the lithofacies of the Ubehebe Formation (Snow et al., 1999). The lacustrine lithofacies is dominated by mudstones, which suggests sample 1-17-3 a mudstone rock with an elevated level of MgO (Snow et al., 1999) and CaO (Table 3-9). The sandstone lithofacies is dominated by sandstone, which suggests sample 2-17-1 is a sandstone with low levels of MgO, FeO, Al<sub>2</sub>O<sub>3</sub> and high SiO<sub>2</sub> (Snow et al., 1999) (Figure 3.16).

### 3.5 Summary

Death Valley is an ideal location for a Mars analogue site because both Earth and Mars share similar geologic processes in a dry and arid environment. The Ubehebe Volcanic Field resembles the Martian features of eroded volcanic craters and/or impact craters. Scientists investigate the depositional features of the maars which can be compared to the eroded features of Mars' wet past. This chapter used data in the form of panorama images, MAHLI images, petrography and XRF report to confirm the morphology and the geologic nature of the Ubehebe craters.

- 1) The results of the panoramas and MALHI images suggest that the subsurface craters are depressions created by phreatomagmatic eruptions, and the mafic fragments which drape the areas in around the craters are pyroclastic fragments. The ash layers, scoria piles, bomb sags, vesicles in the rocks are features of a magma- water interaction that created maars.
- 2) Petrographic observations identify the minerals associated with the sedimentary rocks and igneous rocks. The sedimentary rocks are clasts from the sandstone and

conglomerate parent rocks which agree with the paleo-geology of the area. The igneous rocks are juvenile clast brought by the magma during the explosive eruptions

- 3) Le Bas (1986) Igneous Rock Classification classified two of the samples as basalts and one sample as a trachy andesite. The elements weight percent of the oxides of the samples support the claim that deposits and morphological features have sedimentary lithologies and igneous lithologies.



## Chapter 4: The Game: ‘Hebebot: A Martian Expedition to a Terrestrial Analog’

### 4.1 Introduction

The use of games as an educational tool in schools has increased. This is important because our world is dominated by technology. Kulikova & Maliy (2015) agree that playing games in the classroom increases logical thinking, increases problem solving skills and allows students to be creative. Sometimes teachers face challenges to present certain science concepts to students because of their abstract nature. Vygotsky (1978) agrees that children develop the ability to comprehend abstract concepts through play, and that children can learn by playing science games.

In this thesis, data collected at the five sites at the Ubehebe Volcanic Field was used to develop the game application “Hebebot: A Martian Expedition to a Terrestrial Analog”. This game gives students the opportunity to be part of a virtual world of observing geologic features from hundreds of miles away. The students can think critically as they apply knowledge learned to answer the geologic question of whether the craters at the sites were created by a volcanic eruption or an impact. The knowledge that is required for the game is learned from the lessons designed to provide the criteria for distinguishing volcanic craters from impact craters prior to the playing of the game. The students must understand the differences between the morphology and formation of both maar volcanoes and impact craters, because the craters created by both processes are depressions in the ground. Also, prior to the game, the students must learn about the rovers and their operations on Mars.

### 4.2 Relevance of games in the classrooms

The use of games in the classroom is relevant as society has incorporated the use of technology into most of the ways in which we communicate. Students' interest in games has caused schools to increasingly incorporate technological games in the lesson plans. Earth Science courses are mostly taught through online programs in high school, because it is not mandatory. For a game to be used as an education tool, the game must follow structured rules, defined outcomes, and feedback (Young et al., 2012). In the game application "Hebebot: A Martian Expedition to a Terrestrial Analog" students follow set instructions, gain points and have an energy budget which keeps the game interesting. At the end of the game students receive feedback on their answer choice.

Gee (2003) agrees that an educational game must follow sound learning principles. To play the game created in this thesis, the students must be able to define, explain and recognize the geologic processes of both maars and impact craters, and understand the role of the Martian rovers. We think and understand best when we can imagine a situation which will prepare us for action. Analogous situation through simulation in games help us prepare and execute the actions ahead (Gee, 2003). After reading the instructions of the game application, the students can think of the things which they must first consider. Game players like the sense of control that games provide. The fact that the player can sit comfortably while controlling a rover increases engagement and curiosity. McClarty, (2012) associates students' engagement with students' achievement.

The dynamics of games played in the classroom prepares the players for the world outside of the classroom since games follow set rules or principles. The knowledge learned from playing the game in this thesis draws on the skills of geologists, and other professionals. An understanding of the associated knowledge and skills on which these professions are based

allows the students to internalize how these roles are applied in the real world (Shaffer, 2004; Gee, 2003). The students become a part of a larger community where they simulate the physical environment with the valued practises and the ways of thinking that organize those practises (Shaffer et al., 2005). Teachers facilitate and teach, they are not a part of the audience, therefore game players share ideas, collaborate with peers and participate in discussion forums (Shaffer et al., 2005). These new social language mechanisms and norms are found in the work places as students become a part of the work force.

The game “Hebebot: A Martian Expedition to a Terrestrial Analog” gives students the opportunity to explore relevant to students because topics in Planetary Science as, Planetary Science is not mandated for high school. This research will give students the opportunity to broaden their knowledge of different geologic processes that form volcanic and impact craters and the operations of Martian rovers. The game is designed with the images captured at the Ubehebe Volcanic Field in Death Valley California. Within the game students become part of a virtual tour, as they take a close view of the features of the craters, the rocks and other depositional features. Hopefully the game fosters a new interest and appreciation for Planetary Science.

#### 4.3 The steps/ procedures of developing the game application

The game application ‘Hebebot: A Martian Expedition to a Terrestrial Analog,’ was created using the imprint of a Martian rover- Curiosity traversing the Ubehebe Volcanic Field, Death Valley California. The design and coding of the game application was completed by Fahad Ahmed and Javon Luke, students from the Department of Computer Science at Brock University. Code IDE was used to build, compile and write the application for the game application. Swift Programming language was chosen for this iOS Application. The Site

Explorer application was designed for iPad, iPhone devices, but can be installed and run on any iOS device running iOS version 9.0.

The premise of the game is the student plays the role of an explorer, controlling a rover on a geologic traverse of a Mars-like, cratered landscape. The job of the player is to solve the geologic question of whether the craters are the product of a volcanic eruption or an impact event. This can be solved by going to the 5 sites shown in Figure 4.1. At the sites the player observe the images of rock samples, geologic features within the craters and data describing the geochemistry of the rocks.

The game flow (Figure 4.2) shows the repeated flow of the game: the map screen, explore site (panorama), pick up a rock, select activities view, choose what to analyse, options to move to the next site, view log and solve the problem (Figure 4.2). The application come through high quality photographic images of the Ubehebe craters. The user uses touch gestures to navigate the sites. The hints are stored in a log. The log is used to keep track of geochemical and microimage descriptions of the rocks.



Figure 4.1. Map of the Ubehebe Volcanic Field showing the 5 sites which the rover observed on its traverse. Sites 1-3 are in and around the Little Hebe Crater and site 4-5 are above and in the Ubehebe Crater (Google Earth, 2018).

#### 4.3.1 Steps to playing the game

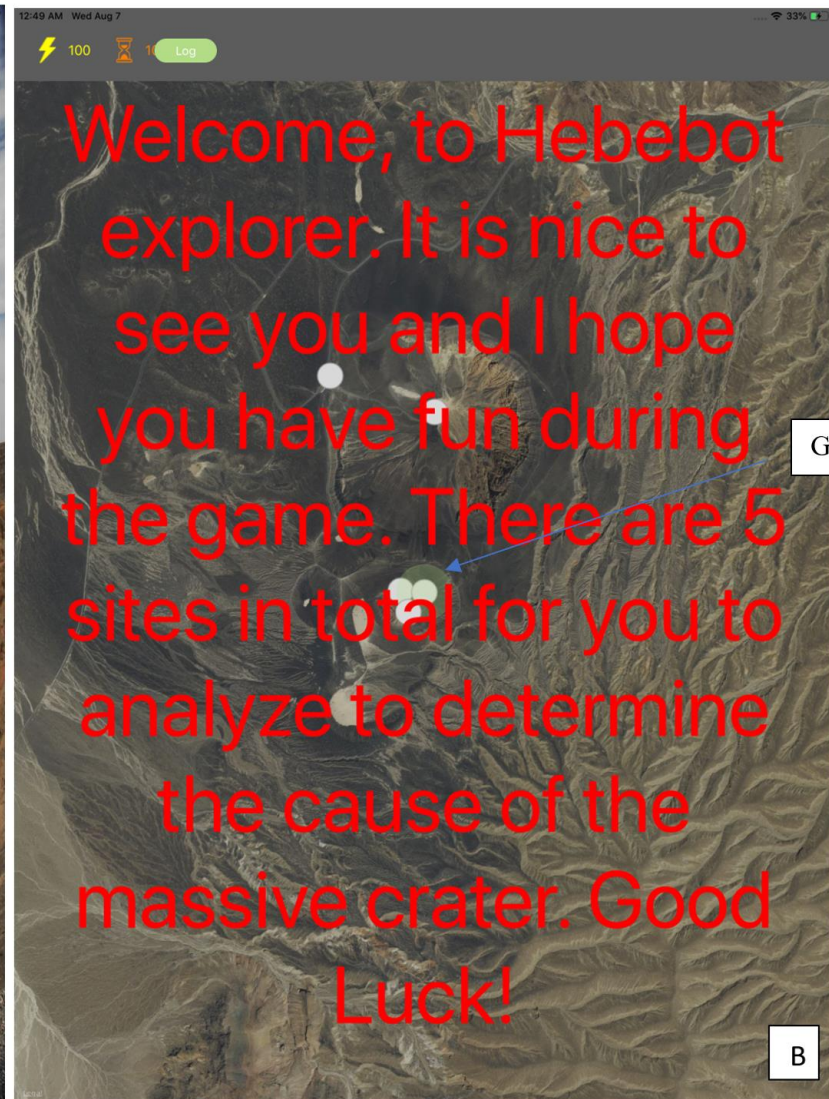
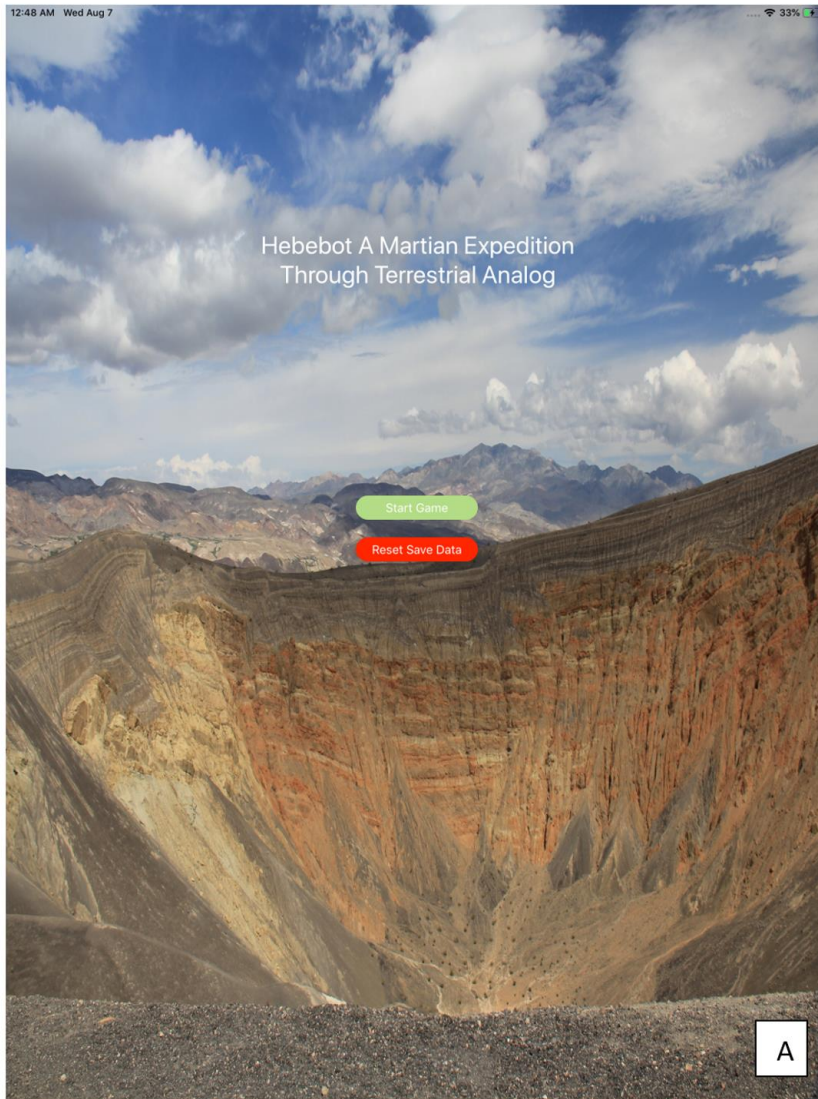
The game follows the steps of a Martian rover on its mission. Before the game is played, the player must read game instructions designed to prepare the player to be successful at the game. At the beginning of the game, the player is provided with 100 energy point and 100 time points to play the game. The player is offered opportunities to gain information in the activities view (microimages and geochemical data) to answer the geologic question. To perform the selected analysis at the different sites will cost the player time and energy.

The game begins by clicking start (Figure 4.2 A). There are 5 sites to be explored. The game prompts the player to click the sites in order, by a green glow over the site. There is a greeting and instructions above the satellite image of that site (Figure 4.2 B). The game proceeds

to exploring the sites, where the player observes the features in the panorama, and/or click on the available rocks to be analysed. Figure 4.2 C shows the white halos which the player must click on to view the selected rock. Figure 4.2 D is the near view panorama in the field of the location of the rocks. You are informed that you can plan an activity after looking at the terrain and/or rocks.

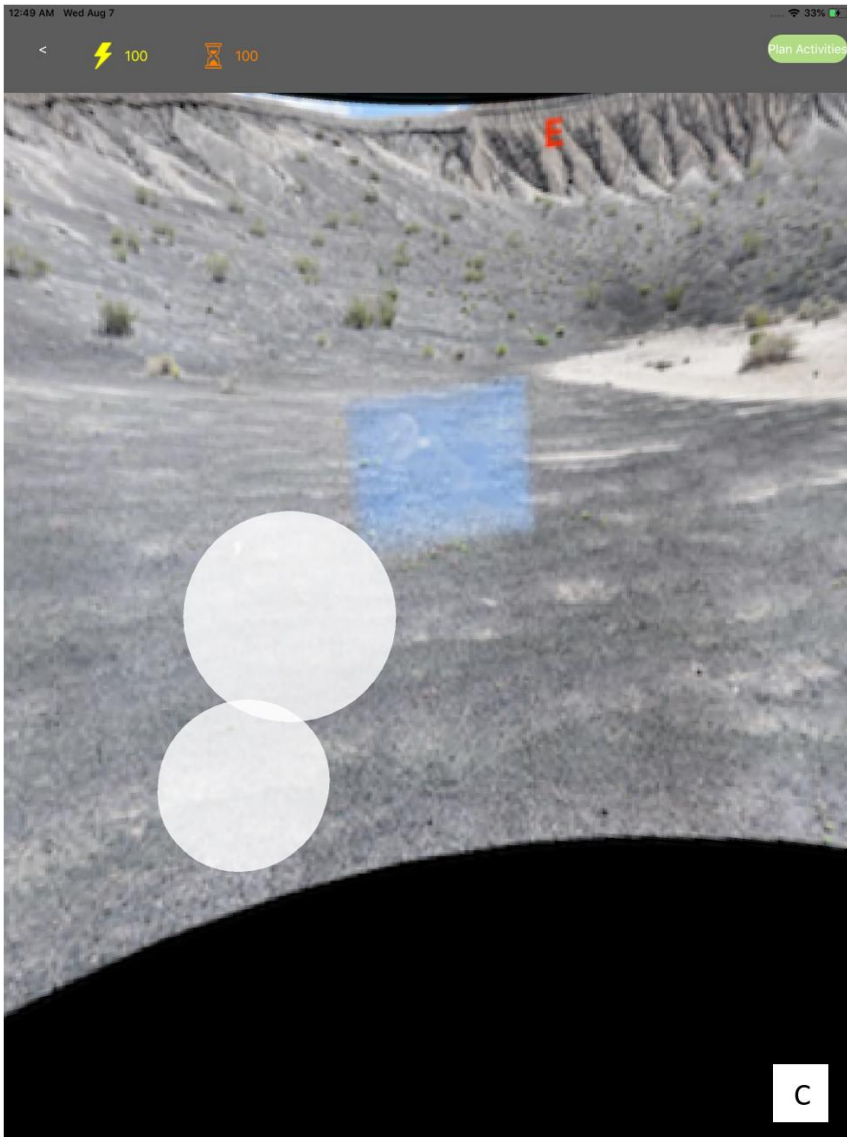
The activities view helps analyse the rocks which helps to understand the geology of the area (Figure 4.2 E). At sites 1-3, where rocks are available for analysis, information on the micro images will cost 3 points each for time and energy. Information on the geochemistry will cost 5 points each for both time and energy (Figure 4.2 F). Figure 4.2 G is an image of one of the rocks to be analyzed. Figure 4.2 H prompts the player to move on to the next site, and what it will cost the player. The game will repeat the same instructions at each site. Sites 4 and 5 do not have rock to be analyzed, therefore the player does not have to plan an activity by analyzing rocks. At these sites, you must observe the features within the crater; the rims of the crater, the orientation of the rock layers within the crater and the rocks and sediments in the crater. After all sites have been explored a message will inform the player as such (Figure 4.2 I). A message will remind the player of the scientific question (Figure 4.2 J). The player must now choose the origin of the crater at each site on the quiz screen (Figure 4.2 K). According to the answers, the definitive answer will be formulated to whether the craters were created by an impact, a volcanic eruption or undetermined (Figure 4.2 L). The final screen will give you your final score, and remaining energy and time bonus (Figure 4.2M). The player has successfully completed the game; ‘Hebebot: A Martian Expedition to a Terrestrial Analog.’



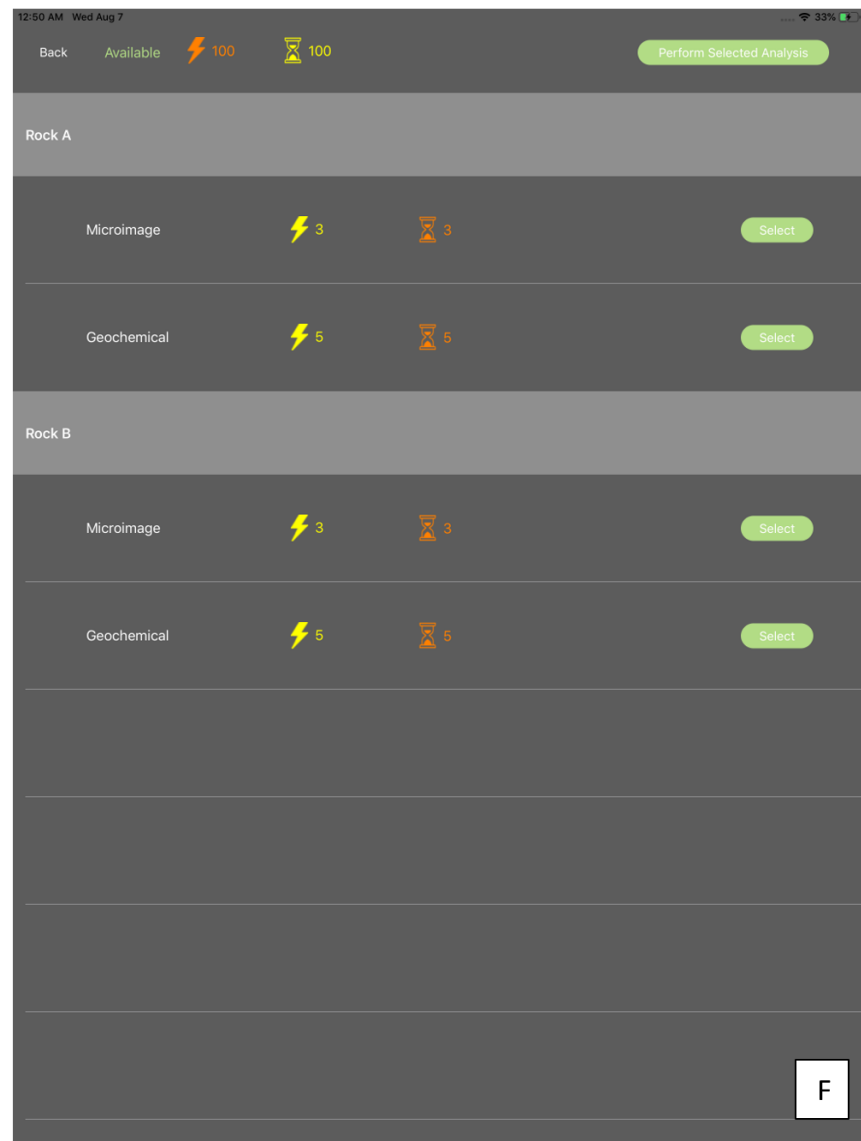
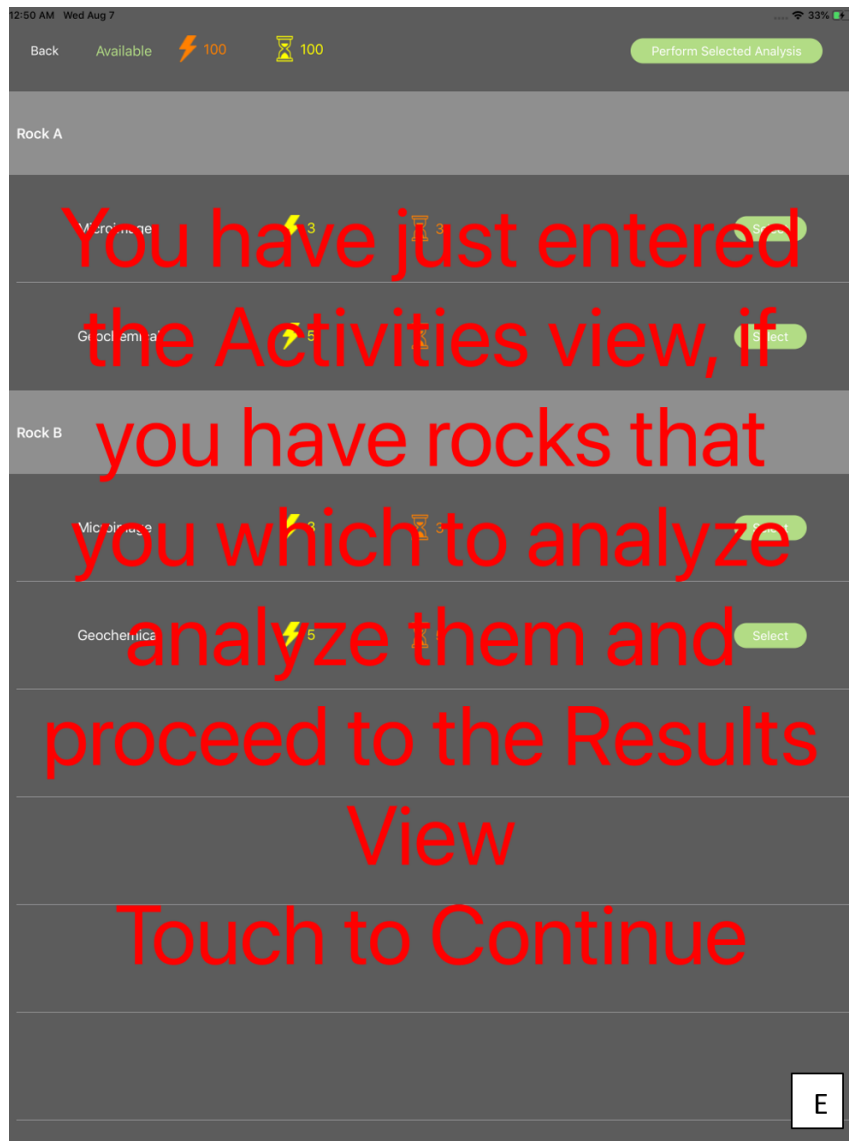


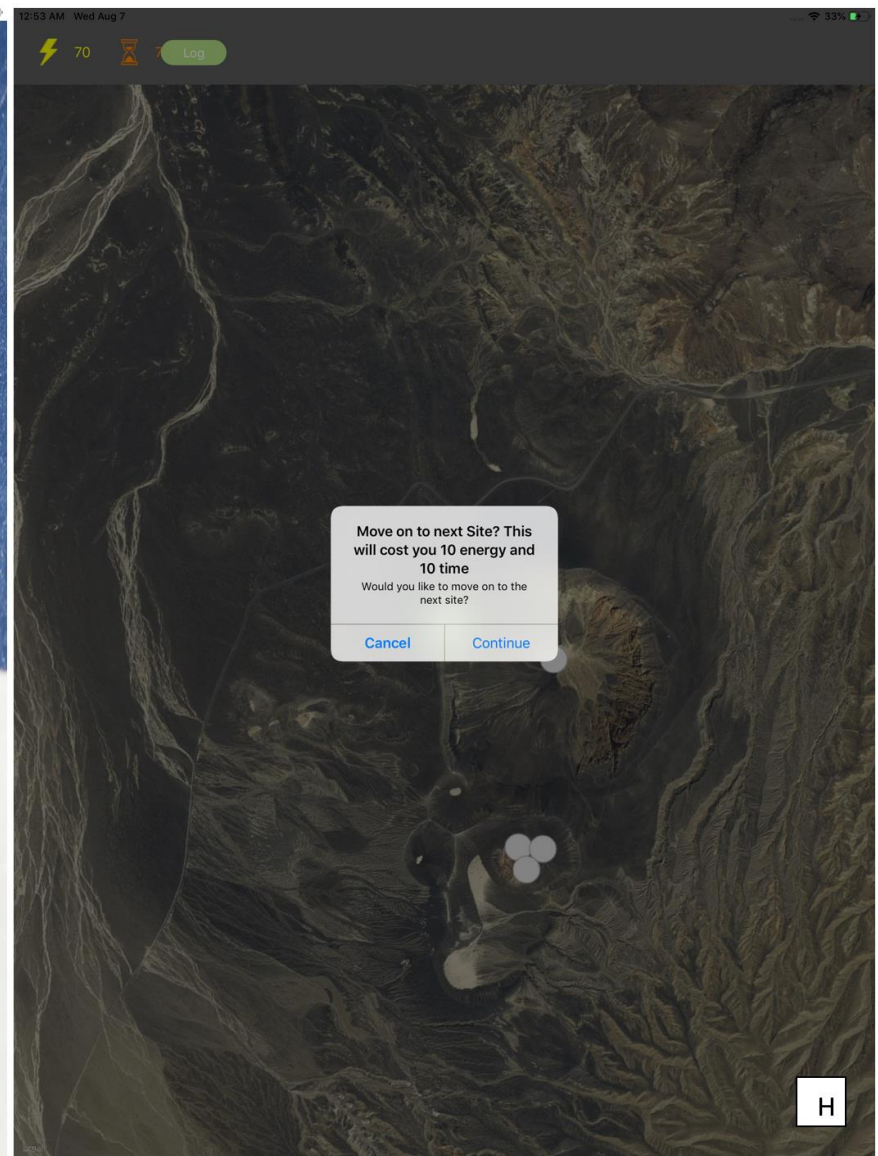
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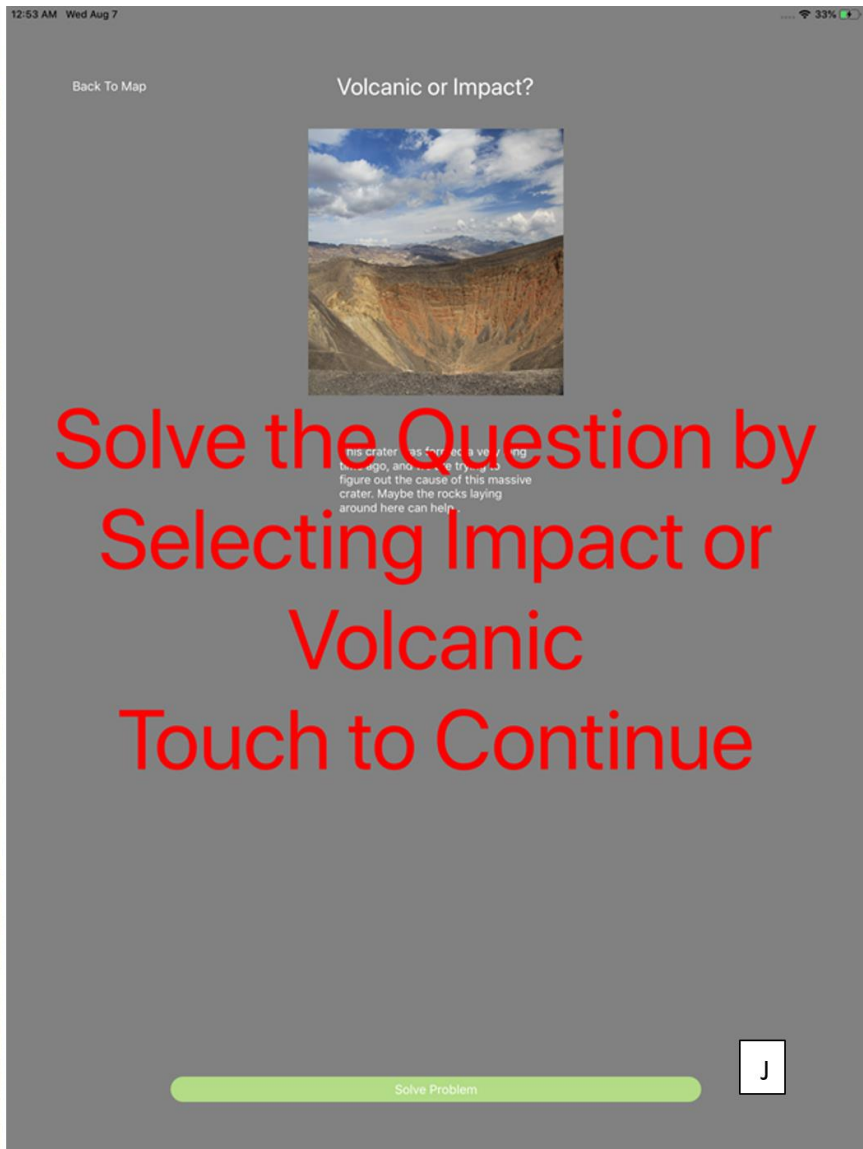
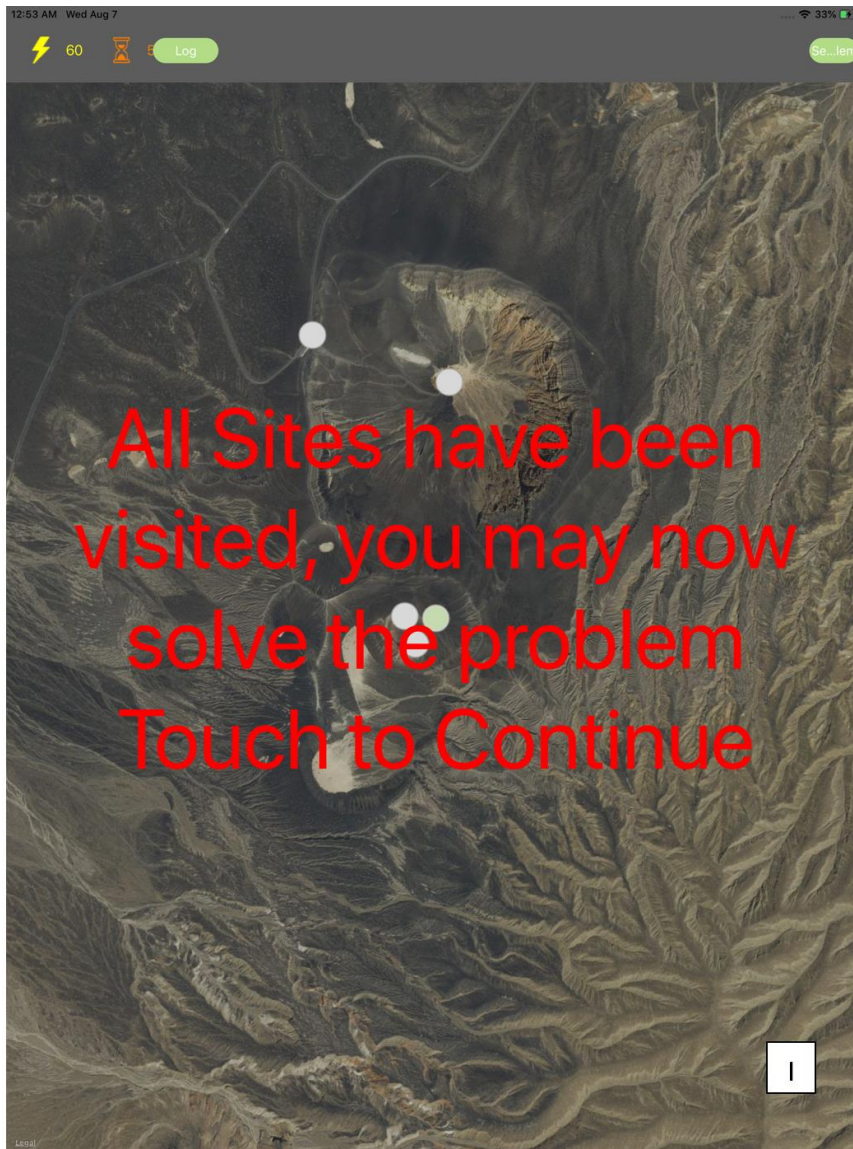


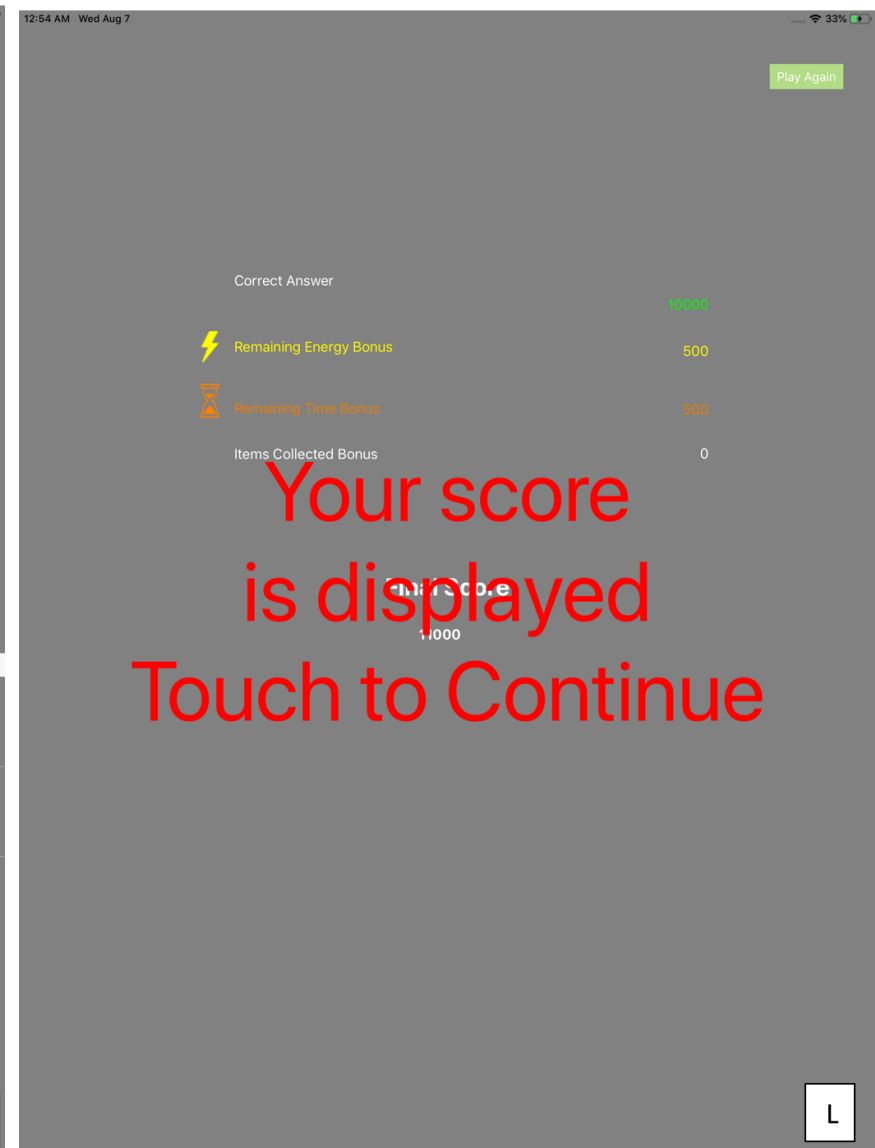
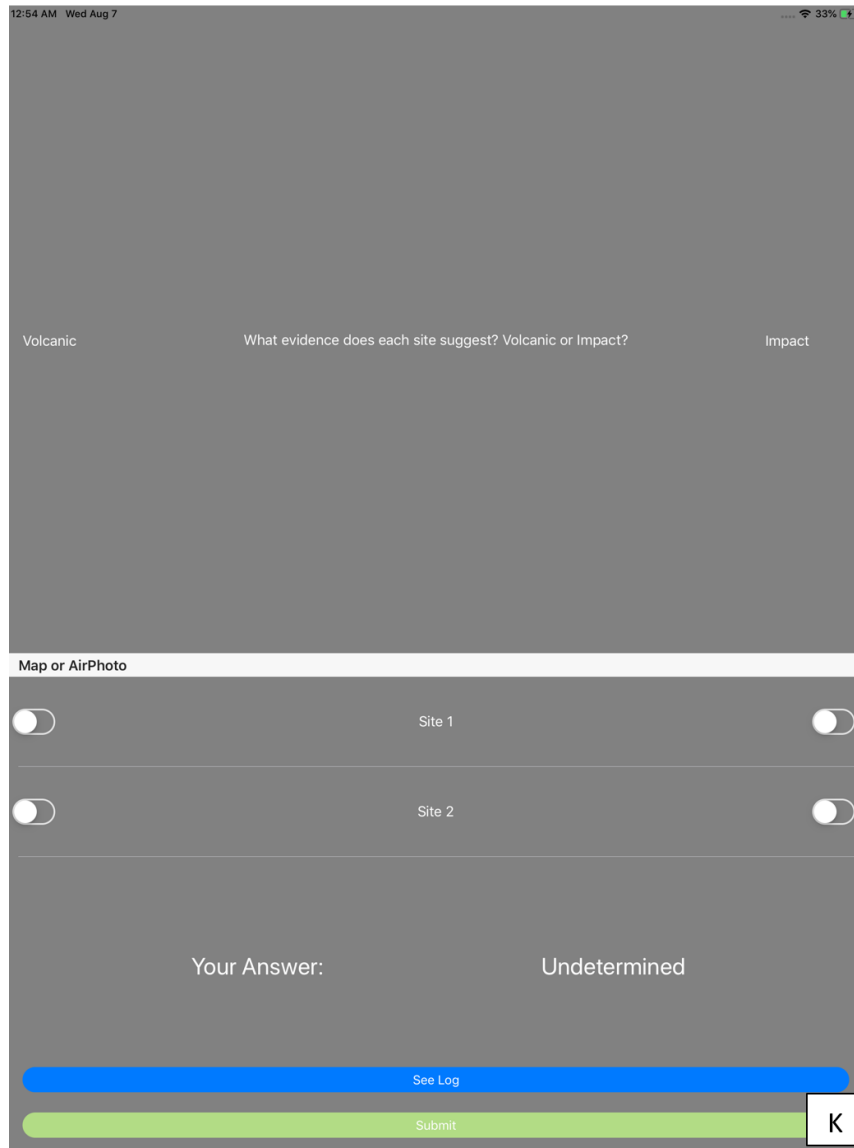












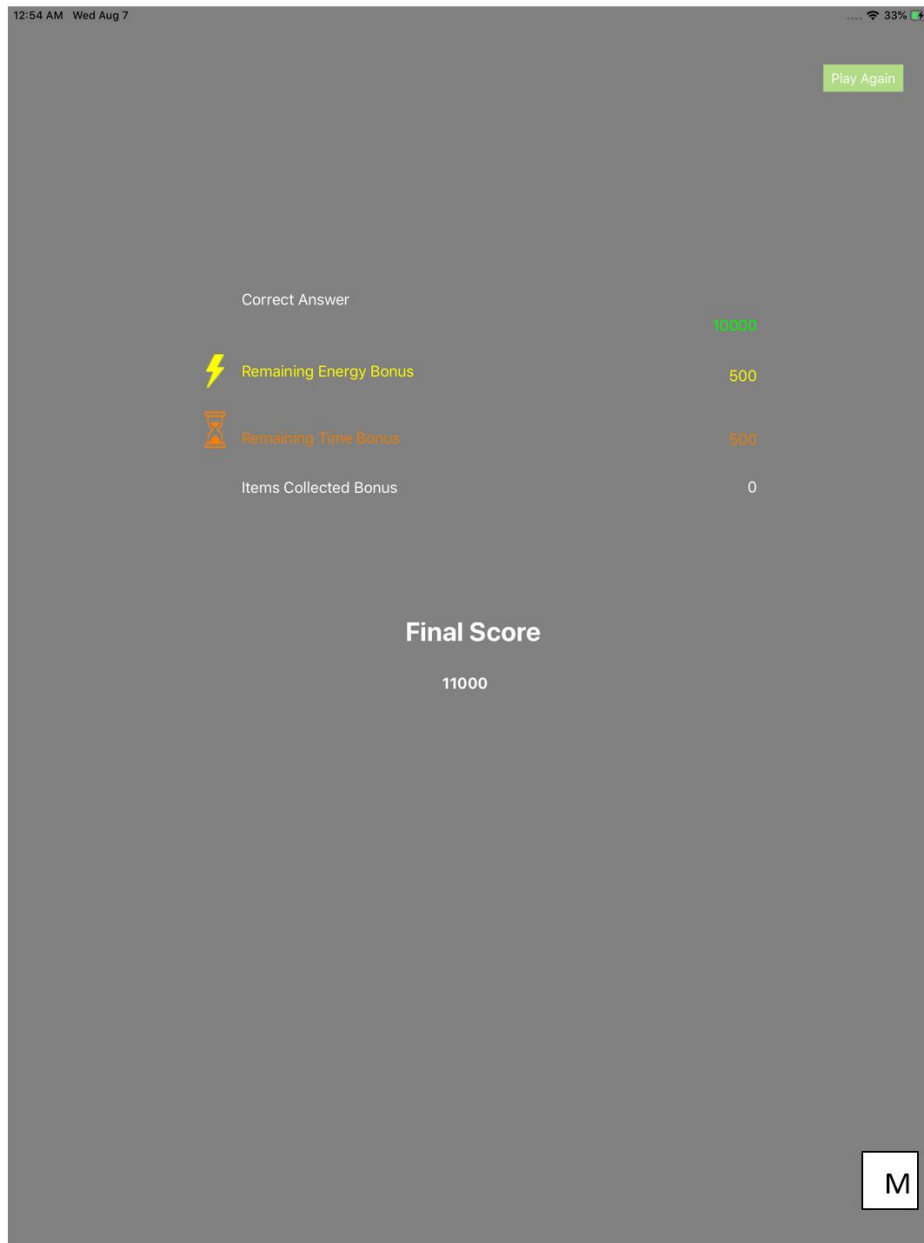


Figure 4.2. Game application screenshots. Image A first slide to start game. Image B welcome slide over field sites. Image C is the slide of the 2 halos indicating the 2 rocks. Image D is the nearfield panorama with the rock locations. Image E instruction to perform analysis of rocks. Image F content on activities view. Image G is enlarged image of rock being analyzed. Image H instruction to move on to next site. Image I instructions that all sites have been visited. Image J instruction to solve the geologic question. Image K quiz view to solve the question. Image L instruction that score is available. Image M final score with available remaining energy and time.

#### 4.3.2 Developing the game with the lesson plans

The purpose of the lesson plans before the game, was to introduce the students with enough information to be efficient players. The lessons were planned to teach the formation processes and physical features of craters formed by volcanic eruptions and impactors. Both impact craters and maars can be easily mistaken for the other, as they both can be similarly modified by weathering and erosion. Besides the fact that both are depressions more evidence must be known to be able to prove the crater in question. In this thesis, the petrology and XRF analysis done on the rock samples collected from Sites 1-3 (Chapter 3), provide the necessary “evidence” for the player to answer the question (solve the problem) of determining the origin of the crater.

Site 1 shows the panorama of the entrance to Little Hebe (Chapter 3, Figure 3.5). The image shows the raised ridges in the background and the crater rims of Little Hebe to the East. In Chapter 1, the lessons explain the formation and features of impact craters and maars; the ejecta for impactors and tephra rims for volcanic eruption. The black material which covers the land and the analysis of the mafic rock with vesicles and the quartzite at Site 1, all prove the nature of the crater.

Site 2 shows the panorama of the top of the Little Hebe (Chapter 3, Figure 3.6). The depositions of tuff rings, bomb sags and lapilli can be seen in the image. In Chapter 1, the lesson on maars described the features of each part of a maar. Also, the short video in the lesson verbalized what can be seen during a phreatomagmatic eruption- Icelandic eruption. The purpose was to identify certain features formed from this style of eruption.

Site 3 shows the panorama of Little Hebe to the east (Chapter 3, Figure 3.7). The thick scoria is seen beneath the layers of ash. Again, the rock that was analyzed is seen in the near view among other lighter colored rocks. The lesson on maar explained that the magma vigorously erupts through the parent rocks, therefore the combination of juvenile rocks is positioned next to parent rocks.

Site 4 shows the panorama of Ubehebe Crater from the west (Chapter 3, Figure 3.8). The scoria piles, Ubehebe crater strata, sandstone basement rocks, and tephra rings are all seen in this image. From the lesson on impact craters in chapter 1, impact craters produce smooth bowl-shaped crater which are deep (Collins et al., 2012). Ubehebe Crater is steep and deep, but the crater walls are not smooth as described for impact craters. The larger impact craters are not smooth, but they are terraced with an uplift or mount in the middle of the crater's floor. Ubehebe crater does not have a terraced wall or an uplift in the crater floor.

Site 5 shows a 360° panorama of Ubehebe Crater taken from the bottom of the crater. (Chapter 3, Figure 3.9). At this position, the depth and width of the crater is seen. A huge white sandstone rock juts out of the wall of the crater. From the lesson on impact craters in Chapter 1, the impactor meets the ground at speeds exceeding 20 kilometers/second (Carr, 2006). This produces kinetic energy which causes the rocks to behave like a fluid (Carr, 2006). The walls of the Ubehebe Crater are uneven. This evidence suggests that the crater was created by a volcanic eruption. Also, the lesson on impact craters show impactites of shatter cones and pseudotachylite veins as features within the craters (Osinski et al., 2006). The Ubehebe craters has no evidence of these features.

#### 4.4 Students playing the game

Four Brock University students responded to the invitation as participants to play the game application: Hebebot: A Martian Expedition to a Terrestrial Analog. The research took place in room D319, McKenzie Chown at Brock University and lasted for approximately 1 hour 45 minutes. The students formally consented by signing the consent form (Appendix C).

The students actively participated in the presentations of the 3 lessons where they asked questions, completed the worksheet and responded to peer activities. The lessons are described in (Chapter 1). The purpose of the activity in the lesson was for the players to learn the skills needed by the rover team during a Martian expedition.

The game was introduced immediately following the 3 lessons. The students paced themselves as they read through the instructions and background information about the objectives of the game. The students took approximately 25 minutes to play the game and during that time they communicated verbally among themselves. The students used their notes on the worksheet while playing the game.

The students completed a questionnaire (Appendix C) which comprised of 10 questions in the format of true or false and number ranking from 1 to 4. The questionnaire questioned students on the efficiency and effectiveness of the game. The questionnaire was completed in approximately 10 minutes.

#### 4.5 Results from the questionnaire after playing the game

The choices made by the students on each question on the questionnaire are presented in data tables and graphs. The responses help understand whether the game was efficient, and whether the information presented was enough to answer the geologic question, of whether the craters were formed by volcanic eruptions or impactors.



**Table 5-1.** Questions 1-5, yes/no responses from the questionnaire

Question number	Questions	YES	NO
Q1	Did you like playing technology games?	4	0
Q2	Was the information shared before the game helpful?	4	0
Q3	Prior to the game, did you know that Planetary Science was a part of Earth Science?	0	4
Q4	Were you introduced to any Earth Sciences in primary or/ and secondary school?	2	2
Q5	Would you have liked to be given the option of Earth Science as a science subject in school?	4	0

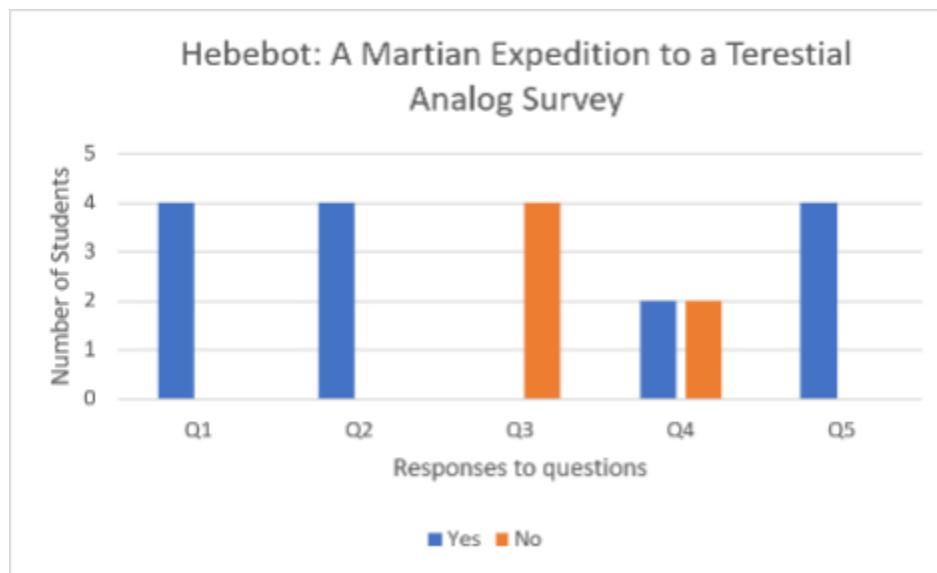


Figure 4.3. The graph shows the results of the yes/no responses made by the students after answering questions 1-5 from the questionnaire.

Question 1 asked students if they liked playing technological games, all participants responded yes. Question 2 asked students if the information shared before playing the game helped, all participants responded yes. Question 3 asked students if they knew that Planetary Science is a part of Earth Science, all participants responded no. Question 4 asked students if they were introduced to any Earth Sciences in primary or secondary school, 2 participants responded yes, and 2 participants responded no. Question 5 asked students if they would have liked an Earth

Science option as a science in school, all participants responded yes. The students' yes/no responses to questions 1-5 of the questionnaire are graphed in (Figure 4.3).

**Table 4-2.** Questions 6-10, 1-4 ranking responses from the questionnaire

Question number	Questions	Excellent	Good	Fair	Poor
Q6	The design and use of information of the game application	1	2	1	0
Q7	The game led to better understanding of how geology is conducted on Mars	2	2	0	0
Q8	The instructions of the game were easy to understand	1	2	1	0
Q9	After the game you want to know more of future space missions	2	1	1	0
Q10	The geologic questions were answerable with the data provided	4	0	0	0

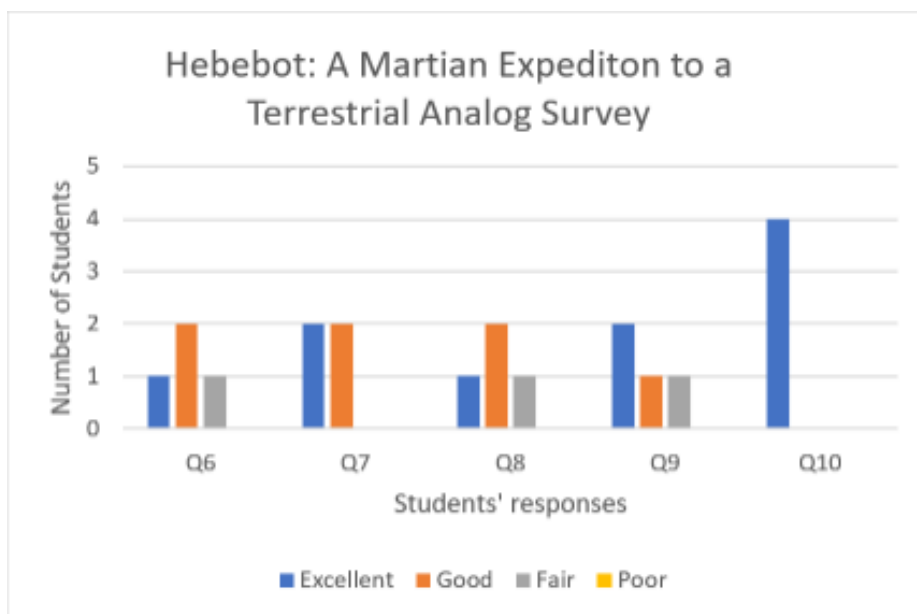


Figure 4.4. The graph shows the results of the 1-4 ranking responses made by the students after answering questions 6-10 from the questionnaire.

Table 4-2 shows the results of questions 6-10 asked on the questionnaire. The columns were: question numbers, questions and the excellent-poor ranking: excellent, good, fair, poor responses to the questions. Question 6 asked students how they rank the design and the use of information of the game application, 1 student's response was excellent, 2 students' response was good, and 1 student's response was fair. Question 7 asked students how they rank the game

leading to a better understanding of Mars, 2 students' response was excellent, and 2 students' response was good. Question 8 asked students how they rank the instruction of the game as being easy to understand, 1 student's response was excellent, 2 students' response was good, and 1 student's response was fair. Question 9 asked students how they rank wanting to know about future space missions, 2 students' response was excellent, 1 student's response was good, and 1 student's response was fair. Question 10 asked students how they rank the geologic question was answered with the data provided, 4 students' response was excellent. The students' excellent-poor ranking responses to questions 6-10 of the questionnaire are graphed in (Figure 4.4).

#### 4.6 Discussion

The students' responses to the questions aid in analysing how comfortable they were with Earth Sciences as a subject and the effectiveness of the game. All 4 students agreed that they enjoy playing technology games. This infers that lessons must incorporate technology to increase participation and interest (Kulikova & Maliy, 2015). All 4 students agreed that the lessons were helpful before playing the game. This infers that the students lacked prior knowledge on the subject. All 4 students disagreed that they knew Planetary Science was an Earth Science discipline. This infers that their knowledge of Earth Sciences is minimal. 2 students agreed to being introduced to Earth Sciences at a previous education institution and 2 students disagreed that they were introduced to Earth Sciences at a previous education institution. This infers that some schools teach the fundamentals of Earth. All 4 students agreed that they would have liked the option of Earth Sciences in their previous education. This infers that Earth Sciences is not explored enough in some elementary schools and high schools to allow students to gain interest and understand the disciplines and opportunities within the different fields.

The response choices of questions 6-10 gave students more options to convey their thoughts on the game. The question on the design of the game application, 1 student's response was excellent, 2 students' response was good, and 1 student's response was fair. This infers that the general design of the game was accepted but can be improved. The question on whether the game led to a better understanding of Mars' missions, 2 students' response was excellent, and 2 students' response was good. This infers that the game helped to understand what happens when a rover is sent to Mars. The question on the instructions of the game application, 1 student's response was excellent, 2 students' response was good, and 1 student's response was fair. This infers that the instructions can be re written for optimum understanding. The questions which asked if one wants to know more about future space mission, 2 students' response was excellent, 1 student's response was good, and 1 student's response was fair. This infers that this research activity brought awareness to Planetary Science. The question whether the geologic question was answered with the data provided, all 4 students' response was excellent. This infers that the objective of the game was 100% successful.

#### 4.7 Limitations of the game

There are a few limitations that players can encounter when playing Hebebot: A Martian Expedition to a Terrestrial Analog. Players can find themselves unable to play to their full potential if they become preoccupied at scoring higher than other players. The player might miss the learning component of the game. Players can avoid the 'rock analysis' because they do not want to spend extra energy and time. Players can spend too much energy at one site and won't be able to visit every site with their remaining time and energy.

Another limitation of the game is, some of the panoramas are not clear. For example, the panorama for Site 2 (Chapter 3, Figure 3.6A) is not clear, as the features on this part of the crater

are not visible. The lack of information does not represent the actual field site. The panorama for Site 1 is hazy (Figure 4.3 C). This is due to the stretching of the image. As a result, the images are not sharp or as focused. This limitation can cause the player to spend more time trying to identify the features at the site. Coding the game with a different layout for the panoramas might prevent the stretching of the panoramas.

#### 4.8 Summary

The use of technology in the form of games in the classroom allows students to learn abstract concepts and to participate in a virtual world outside of the classroom. Games are highly interactive and fun while learning takes place (Vygotsky, 1978). The game application Hebebot: A Martian Expedition to a Terrestrial Analog, gives participants the opportunity to answer a geologic question, constructed with data collected thousands of miles away from the classroom.

- 1) The game application was developed by Fahad Ahmed and Javon Luke. These Computer Science students built the application to make use of the photographic images, XRF data and micro-images collected from the Ubehebe Volcanic Field. The game flow formatted the sequence of commands by following the codes.
- 2) To play the game, the player must read informative slides on the mission, objective and instructions of the game. The player navigates through 5 sites to answer the geologic question, whether the craters were impact or volcanic in origin? Sites 1-3 have rocks to be analyzed which helps understand the geology of the area. The game will prompt the player to open an activities log find more data about the rocks. Sites 4 and 5 are panoramas of the crater and has no rocks to analyze.
- 3) The information in the 3 lessons (Chapter 1) was used to teach the formation and morphology of impact craters and maars to provide background information on the

operations of the rover. Sites 1-5 were designed to use the information taught in the lessons.

- 4) There are limitations of being preoccupied with spending too much energy and time, and not being able to finish the game. Not exploring the game to the full because of the fear of low levels of energy and time. Also, due to the panoramas not fitting properly in the application, the clarity of the panorama prevents the player from successfully viewing the morphology in the panoramas.
- 5) Four students at Brock University completed the 3 lessons, played the game and completed the 10-questions questionnaire. The results are represented in tables and graphs. The results suggest that Earth Sciences is not explored enough as a Science in schools. Also, the results suggest that the geologic question in the game was answered from the data provided.

## Chapter 5: Final Discussion and Overall Conclusion

### 5.1 Final Discussion and Overall Conclusion

The game application, Hebebot: 'A Martian Expedition through a Terrestrial Analog' was developed with analyzed data collected from the Ubehebe Volcanic Field, Death Valley California. The data was used to answer the geologic question of whether the craters are volcanic or impact. The geologic location was chosen because of the similarities of in the appearance of impact craters and maars.

The rock sample analysis through petrologic images and XRF report, and photographic images of the morphology of the site agree that the geologic features are those of maars. Valentine et al., (2017) suggests that the tephra rims of the maar crater were produced by erupted pyroclastic deposits of both accidental and juvenile materials, caused by the phreatomagmatic explosions. White & Ross, (2011) suggest that low temperature pyroclastic density currents contain lithic material which produce deposits containing lapilli and vesiculated tuff caused by water in the currents. The tephra rims and the walls of the Ubehebe craters are laden with the tuff breccias and lapilli tuffs. The photographic images captured the location of these deposits at the field site. The petrographic images of the rock samples suggest that some of the rocks are sedimentary- parent rocks and some of the rocks are igneous- juvenile clasts. The results of the igneous rocks showed evidence of phreatomagmatic-explosive interaction of water and magma- the vesicles, volcanic clasts, and plagioclase microlith. XRF analysis show the oxides and trace elements which favors the mineral chemistry of basalts and sandstones. The classification of volcanic rocks, Le Bas, (1985) TAS plots identified 3 of the 6 rock samples as basalts. This indicates the chemistry of the erupted magma at Ubehebe maars.

This thesis shared information that show the Ontario Science Curriculum and the Houston Independent School District Science Curriculum. It can be concluded that Earth Science is not a mandate for high school student to graduate, therefore not much is done for school to teach Earth Science or to interest them in pursuing courses in college. It is the hope that this game created an avenue to explore Planetary Science in the future.

Without proper scientific investigation of a surface crater, the feature can be interpreted as a maar or an impact crater. The students who played ‘Hebebot: A Martian Expedition to a Terrestrial Analog’ were able to differentiate between a maar and an impact crater and concluded that the Ubehebe craters are volcanic. The morphology at both crater types have depositional features which make each unique to the process by which it was formed.

Gee, (2005) agrees that games can serve as assessment tools. Games are a fun way to share knowledge in an entertaining and engaging way to students. This thesis gave students an opportunity to learn topics in Earth Science- Geology and Planetary Science, through the game. The students participated in 3 lessons, which taught the content on the game. The game served as an assessment tool. The student’s responses to a questionnaire at the end of the game, suggest that the analysed data used to develop the game was effective.

## 5.2 Limitations of the study

There were a few limitations in this study, which could have influenced the results or/ and interpretations. The instrument used to capture the panoramas- Gigapan, was not calibrated to the correct settings, the Gigapan stitching program was unable to build the mosaics of the features, therefore the preciseness and the clarity of the panoramas are lacking. Stitching the panorama required another software, which was added cost and was time consuming. There is a lack of a larger group of students to play the game. It was difficult to get students to sign up for 2



hours to be participants of the survey. A bigger group of students would give a better representation of the student body and their opinions. The game application was designed only for an Apple platform . This means that coding, editing and other modifications could only be done on an Apple computer or laptop. The panorama files were very large, therefore adding them to the game sometimes caused the game application to crash. On the day the students played the game, the game application crashed and had to be restarted.

### 5.3 Future Work

Future work on the game application requires new panoramic images, recoding of the game to prevent crashing caused by the large files. Also, the opportunity to include another feature, alluvial fans in the game is possible, as data for future game development on an alluvial fan in Death Valley is in Appendix A in this thesis. A bigger survey group will allow more responses on the effectiveness and efficiency of the game. Adding a qualitative component of the questionnaire will allow open ended questions. This game has the potential to be incorporated in an Earth Science high school course.

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# Appendix

## Appendix A

### **Alluvial Fans Show Evidence of Water**

The presence of alluvial fans on the Martian surface is an indication that flowing, liquid water was once present. The findings of many alluvial fans near Martian craters has led geologists and scientists to continue their quest to find evidence of past life on Mars. Alluvial fans are found on Earth and have a few similarities to those on Mars. Moore & Howard (2004), described alluvial fans as landforms that were created by the action of water interacting with the land and transporting that material down the sides of mountains. Alluvial fans form where there is a great relief contrast in the land and little precipitation occurs. Death Valley is known for its hot and dry weather, but when it rains in the mountains, the water rushes down-stream as sudden flash floods. The flash flood transports rocks, pebbles, sand, silt and mud to the base of the mountain (Moore & Howard, 2004). The materials are deposited in a wedged shape at the base of the steep hill or mountain (Moore & Howard, 2004). Alluvial fans are common along the base of the mountain ranges in Death Valley National Park. The sorting of the deposited materials is seen on the base of the fan.

### **Alluvial Fan in Gale Crater, Mars**

The study of alluvial fans on Mars aids in the understanding of Martian history and the presence of water. Like on earth, alluvial fans on Mars are located at the base of steep hills/mountains. On 6 August 2012, the Mars Science Laboratory (MSL) rover, Curiosity, landed in Gale Crater near an alluvial fan called the Peace Vallis Fan (Figure 1) (Palucis et al., 2014). Gale Crater is 155 kilometers in diameter crater, created from an impactor ~3.6 billion years ago (Grant et al., 2014). Gale Crater is in the Aeolis Quadrangle, an area between the highly cratered

southern highlands and low-lying northern lowlands called the Dichotomy Boundary (Anderson & Bell, 2010). The Dichotomy Boundary refers to the transition between the Southern Highlands and Northern Lowlands. Curiosity travelled to the east on its traverse where gravels, conglomerates and clay-bearing mudstones in Yellowknife Bay were encountered. These observations confirmed that further investigations in the area can identify fluvial facies (Palucis et al., 2014).

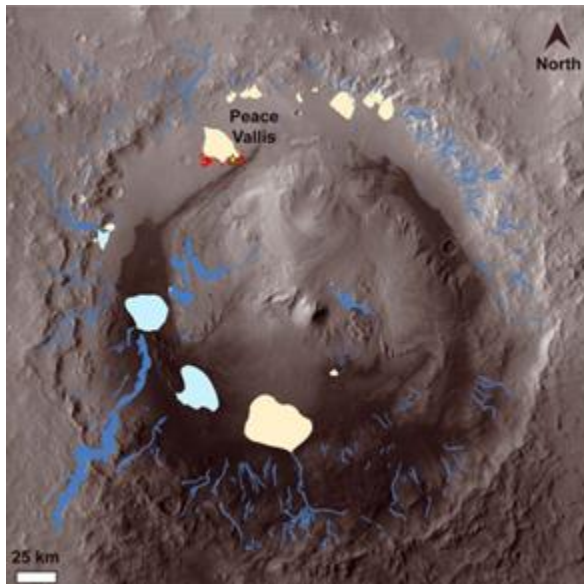


Figure 1. Geologic map showing an aerial view of the alluvial fan at Gale Crater. The (dark blue) represents the valleys and canyons, (tan) represents the fans, (light blue) represents the fan deltas. The Peace Vallis delta is labeled.

### **Alluvial Fans in Death Valley, California**

The alluvial fans in Northern Death Valley, California are extensive, well developed desert pavement at the base of the Black Mountain range and Panamint Mountain range. Staley et al. (2005), suggests that the fans are Holocene in age. The Black Mountain range lies to the east of Death Valley and the Panamint Mountains lie to the west. The small semicircular fans on the west front of the Black Mountains contrast with the fans on the east from the Panamint Range (Denny, 1965). At the base of the mountains, the

horizontal soil profiles are carbonate dominated, filled with silt, calcium carbonate and salt (Knott et al., 2005). At the base of the Black Mountain range, there are at least 12 alluvial fans from Badwater to Mormon Point (Denny, 1965). Figure 2 shows the geologic map of alluvial fans in the Black Mountain range; (a) Trail Canyon, (b) Grotto Canyon, (c) Deadman Canyon, (d) Badwater. This thesis will show the depositional environment of a small fan near Badwater. Blair & McPherson (1994) labelled the key morphologic features of the alluvial fan: “drainage basin, feeder channel, apex, incised channel, distributary channels, intersection point, active depositional lobe” (MohdFauzi, 2012).

Figure 3 illustrates the depositional environment and the types of depositions of a typical alluvial fan. The coarse materials such as un-weathered gravel, weathered gravel on desert pavement, and gravel in abandoned wash are deposited in the above order. The evaporates are deposited the farthest from the mountain. A mountainous desert like Death Valley provides ideal conditions for alluvial fan development (Sohn et al, 2007).

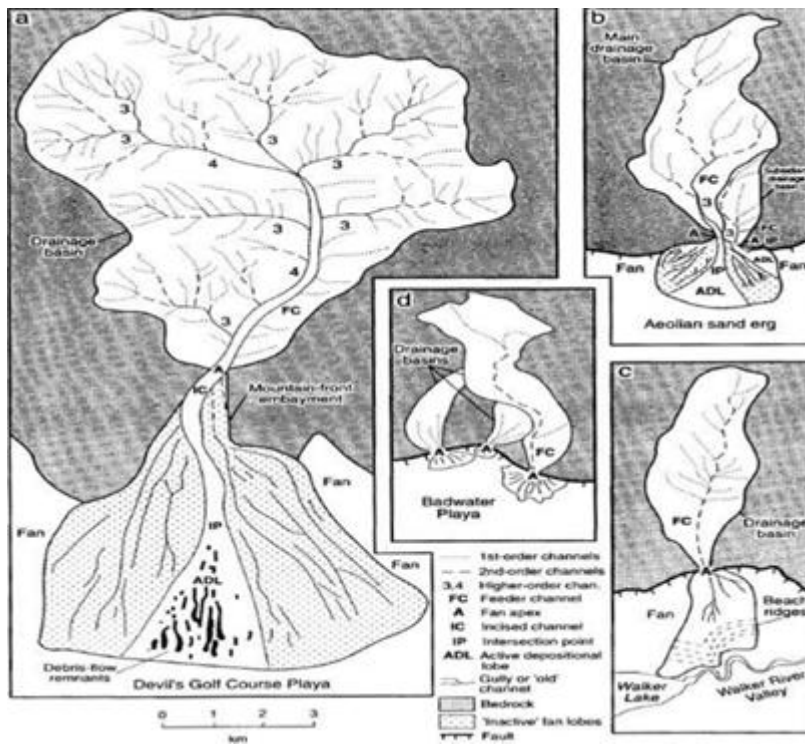


Figure 2. Sketches of geologic maps of four alluvial fans in Death Valley: a) Trail Canyon, b) Grotto Canyon, c) Deadman Canyon, d) Badwater. The abbreviated meanings are at the bottom of the document (Blair & McPherson, 1994).

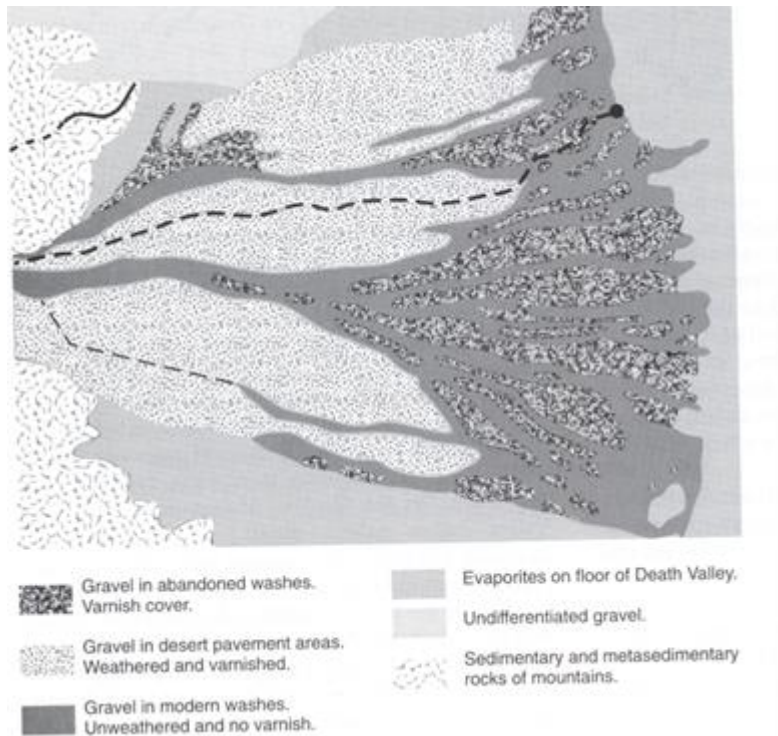


Figure 3. An alluvial fan in Death Valley, California showing the depositional environments and the assortment of deposits on the desert floor (Denny, 1965).

### **Alluvial Fan images results**

The information gathered in Table 1 includes the GPS locations of the three stops at the alluvial fan. The 180° panorama of the alluvial fan captured the top of the mountain, the wedged fan, the depositional environment and the dried, cracked salted evaporated base the farthest away from the mountain (Figure 6). The near view panorama captures the combination of pebbles, carbonate rocks, igneous rocks, and organic matter (Figure 7). The residue of salt is seen along the cracks of the dried silt/mud ground (Figure 5-F). The deposition of the rocks at the base of the fan shows that there was once moving water which transported the material from the higher elevation down the slope to the base (MohdFauzi, 2012).



Figure 4. Aerial image of the alluvial fan in Death Valley. West of the alluvial fan is the steep mountain from which the water transports its load onto the base of the mountain. The road run north-west to south-west of the fan. The wedged shape feature can also be seen in the image (GoogleEarth, 2013).



**Table 1.** GPS Locations, Compass bearings and Description of Sites at the Alluvial Fan, Death Valley California

Site information	Stop 1	Stop 2	Stop 3
GPS Location	N 36°07.003' W 116°44.682'	N 36°06.804', W 116°44.474'	N 36°06.832', W 116°44.455'
Compass Bearing Infinite panorama Near field panorama	0°- 95°	10°-75° 180°- 210°	15°- 95° 30°-75°
Description	The base of the moutains moving into the depostional environment.	Depostional environment; rocks and evaporites on ground.	Depostional environment with rocks and gravel.

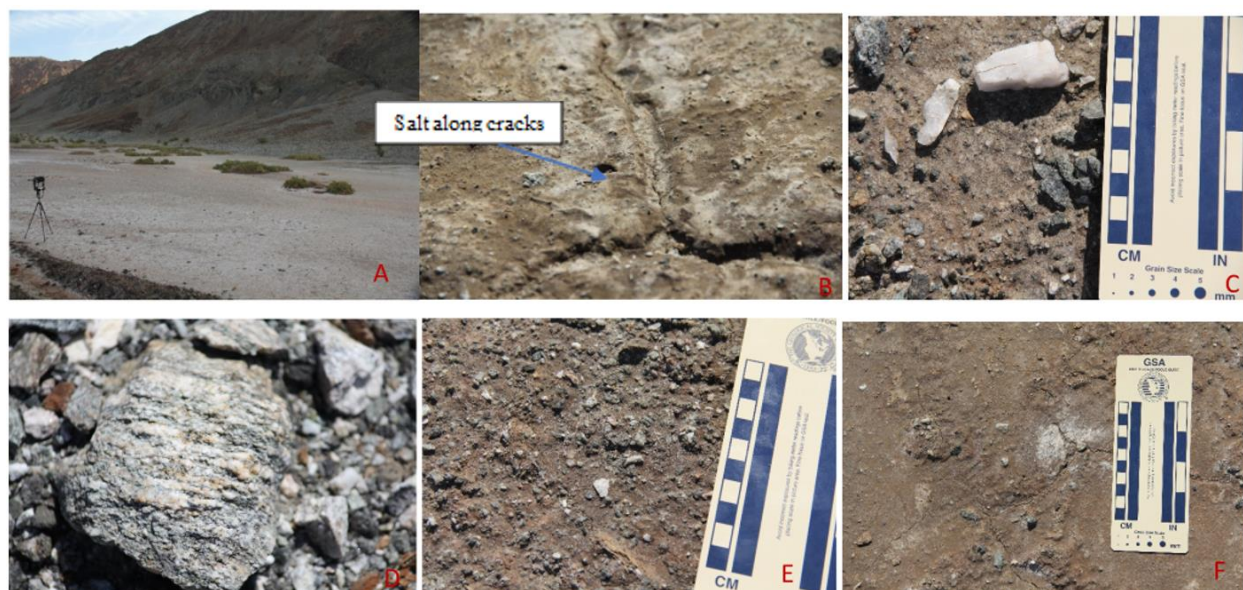


Figure 4. Alluvial fan images. Image- A: the view of the alluvial fan and the depositional environment. Image B- cracks in ground, image C- MAHLI of a halide rock, image D-rock at the base of the fan, image E- rock fragments deposited further away from the mountain, image F- salt deposits on dried cracked ground.



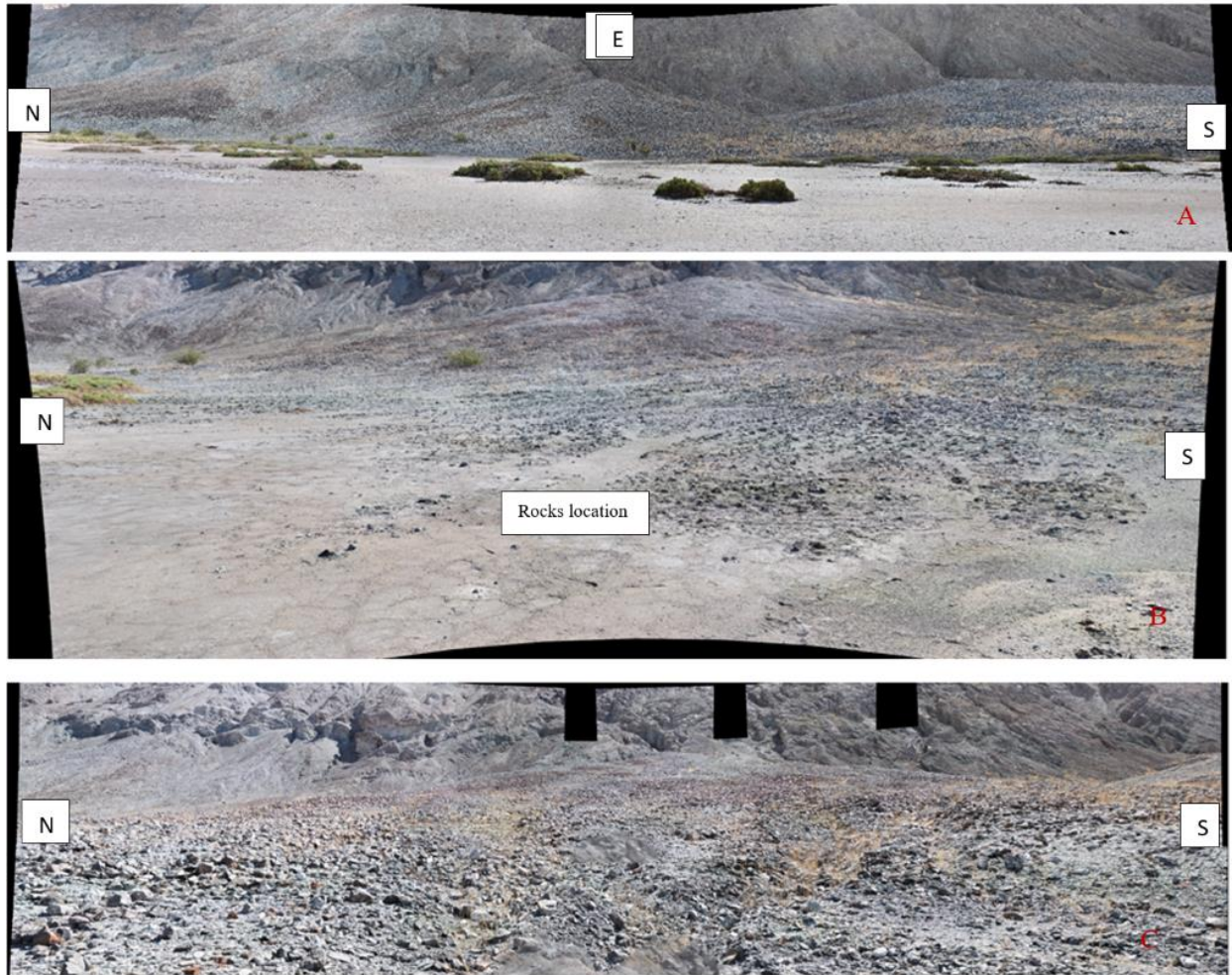


Figure 5. Alluvial fan, Death Valley. Image A 180°panorama of Stop 1. Image B 180°panorama of Stop 2. Image C 180°panorama of Stop 3. In each panorama the orientation (North, South, East or West) of the picture is indicated.

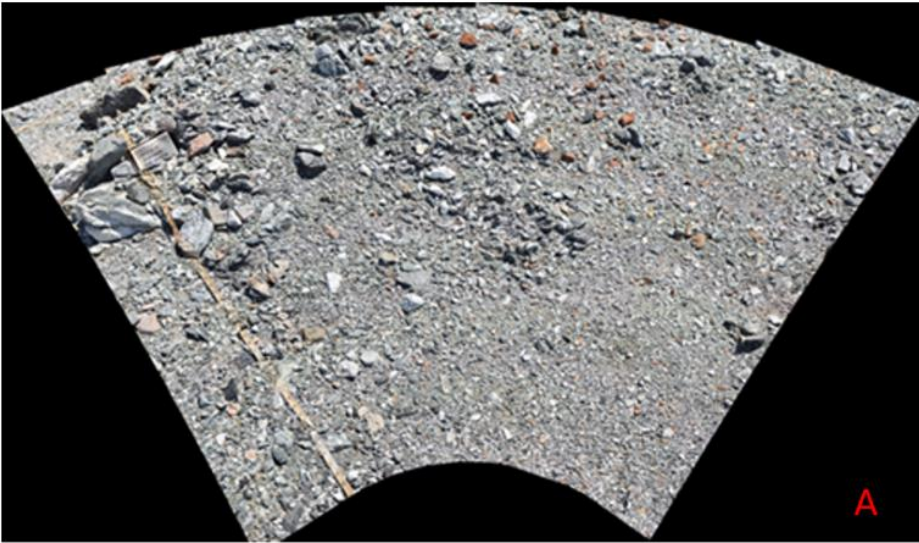


Figure 7. Image A- Near field panorama and rock materials on the alluvial fan. Image B- halide rock next to black rocks wedged in the ground. Image C- rock fragments are ~1-2 centimeters.

### **Alluvial fan Discussion and Summary**

The panoramas of the alluvial fan suggest that material was transported down the slopes of the mountains by moving or flowing water. The depositional environment at the base of the alluvial fan was deposited with the largest rocks closest to the mountain and the gravel, pebbles and silt the farthest away. Laronne & Reid, (1993) agree that an arid to semi- arid mountain

region favors alluvial fans depositions. This environment is evident in Death Valley's alluvial fans. The lack of vegetation makes it easier for sediments to be eroded during intense flash floods. The wide-open area at the base of the fan is covered with dried cracked silt. There are areas where salt can be seen along the cracks. The salt indicates that water was present, then evaporated (Figure 6B). The loss of energy at the lower relief region is responsible for the wide silt/ mud base, as the larger materials were deposited first (Harvey, 2011). The results of the panoramas and MALHI images suggest that alluvial fan was created by the onset of a flash flood in an arid mountainous region. The depositional environment and crusted salt ground at the base indicate that the paleoenvironment was once wet.

## Appendix B

### **The Rovers**

#### **Pathfinder lander and Sojourner rover 1997**

It was necessary to have a device that could move around on the Martian surface and this requirement led to the introduction of a robotic vehicle called a rover (Copper, 1998). A rover can travel across the Martian terrain while it collects data, such as images and chemical analyses. On July 4, 1997, Pathfinder lander which included the Sojourner Rover landed on Mars and began to explore (Copper, 1998). This was the first time a rover arrived on Mars. The Sojourner rover explored Ares Vallis, an area close to the landing site in Chryse Planitia (Matijevic et al., 1997). The Sojourner Rover was equipped to roam the Martian surface. This rover is a six-wheeled vehicle, 68 cm long, 48 cm wide, 28 cm high, and weighs 11 kg. The following is the list of equipment on board the rover; “Ultra High Frequencies (UHF) modem, and batteries, A Gallium Arsenide solar panel and Material Adherence Experiment (MAE) are on the top of the Warm Electronics Box (WEB) A pop-up UHF antenna, Alpha Proton X-Ray Spectrometer (APXS), two black and white cameras, and laser stripers used for obstacle avoidance” (Copper, 1998). The instruments aboard the rover made it possible to discover and communicate that the rocks at the Ares site as pebbles from conglomerates. This suggested that water existed for conglomerates to be formed. Pathfinder landed in a flood plain at Ares Vallis. The surface is categorized as a depositional plain, covered with sedimentary deposits of sub angular to sub rounded pebbles, cobbles, and boulders. The disturbed soil contained elevated levels of sulfur mixed with fragmented basaltic materials from volcanoes, while the unaltered rocks contained low levels of sulfur (Carr, 2006). Sojourner helped scientists understand Mars’ history of floods, erosion and fluvial activities (Matijevic et al., 1997). The

Rover Control Workstation (RCW) was used to create commands to control the rover's daily activities. The Earth-based teams planned a day's worth of activities for the rover, after they received information from the lander (Copper, 1998).

### **The Opportunity and Spirit Mars Exploration Rovers**

The Opportunity and Spirit Mars Exploration Rovers (MER) are called "twin rovers," as they are identical in structure and mission. Their mission was to search and characterize the Martian surface for rocks and soil which give clues to a wet paleoenvironment. They landed at opposite sides of the planet in areas that suggest water in the past.

On January 4, 2004, the Mars Exploration Rover Spirit landed in Gusev Crater. Rocks examined by Spirit contained dark fine grained vesicles with origin of basaltic lavas (McSween et al., 2004). Specifically, float rocks dominated the plains and the soil came from olivine basalts (Morris et al., 2008). Spirit's principal objective was to search for the evidence of water, past and present climate and whether life can be revived on Mars (Squyres et al., 2004). On January 25, 2004, Opportunity landed at Meridiani Planum (Squyres et al, 2006). The lander landed in the southern latitude, in an impact crater approximately 20 meters in diameter. (Squyres et al., 2006). Opportunity's main goals were to investigate the geologic record at that site, to assess past environmental conditions and their suitability for life. The rover used a remote sensing device mounted on its arm to select rock and soil targets (Squyres et al, 2006). On this traverse, investigations were made which included the geology, geochemistry and mineralogy of Meridiani Planum, and evidence of past interaction of surface and subsurface water.

The two rovers were equipped with scientific instruments, which include "Panoramic Cameras (Pancam), Microscopic Imager (MI), Rock Abrasion Tool (RAT), Alpha Particle X-

ray Spectrometer (APXS), Mossbauer Spectrometer (MB), and miniature Thermal Emission Spectrometer (mini-TES), nine cameras (four stereo pairs and one micro imager) and an imaging system on the lander,” (Squyres et al, 2016). There is a high-resolution imaging system mounted on the rover’s arm, also known as the Instrument Deployment Device (IDD) (Herkenhoff et al. 2003). These instruments were selected to mimic the capabilities of a field geologist, as the Martian atmosphere is inhospitable for the survival of humans.

### **Mars Science Laboratory (MSL)**

On August 6, 2012, the Mars Science Laboratory (MSL) Curiosity Rover landed in Gale Crater on Mars and delivered the most technically advanced geochemistry laboratory sent to another planet (Grotzinger et al., 2012). The goal of the mission is to understand the past habitability by investigating the strata at Mount Sharp (Grotzinger et al., 2012). The Curiosity Rover has a total mass of 899.2 kg, 2.8 m width, 3 m length (4.7 meters long with robotic arm extended), 1.1 meters top deck height, 2 meters total height, and 75 kg instrument payload (Grotzinger et al., 2012).

Curiosity is currently exploring Mount Sharp, a mountain of ancient, relatively flat-lying strata extending 5 kilometres above the elevation of the landing site; the lower strata of the mountain show a progression with relative age from clay-bearing to sulfate-bearing strata, separated by an unconformity from an anhydrous stratum (Grotzinger et al., 2012). At Yellowknife Bay, Curiosity explored a lacustrine mudstone. This was the best evidence in support of habitability on Mars. (Williford et al., 2018). This rover drilled three drill holes into the ground, two at Yellowknife Bay named 'John Klein' and 'Cumberland', and the third, named 'Windjana', which lies in the sandstones of the Kimberley formation (Abbey et al., 2019). Curiosity came upon a rock ~282 meters away from the landing site named Jake\_M

(Grotzinger, 2013). The rock is a dark, macroscopically homogeneous igneous rock. Jake\_M is highly alkaline and fractionated (Grotzinger, 2013). Jake\_M's closest terrestrial comparison is a mugearite and research has labeled the Jake\_M as a mugearite (Stolper et al., 2014).





**Consent form to participate in a Research Study with Earth Sciences at Brock University**

**Title of Study (Hebebot: A Martian Expedition to a Terrestrial Analog)**

**Principal Investigator: Mariek Schmidt (supervisor), Earth Sciences Department, Brock University, 905-688-5550 ext.3527**

**Student: Aileen Williams**

**The study has been reviewed and received ethics clearance through the REB (file # 18-130 – SCHMIDT.)**

You are invited to participate in a research study conducted by Aileen Williams as part of her master's thesis. The purpose of this research is to bring an awareness of Planetary Science as an option for a university degree and the opportunity to test this new game. Students will play the game "Hebebot: A Martian Expedition to a Terrestrial Analog," to answer the geologic question, whether the craters in the surveyed area are volcanic or impact.

Your participation will involve being a participant in 3 mini lessons teaching content of Earth and Mars, the playing of the game application, and completing a questionnaire at the end.

The amount of time required for your participation will be 1 hour and 30 minutes for the lesson plans, 10-15 minutes to play the game and 5 minutes to complete a questionnaire comprising of 10 questions in the format of true or false and number ranking from 1-4. This will be on June 19<sup>th</sup>, 2019, from 6 pm to 7:30 pm. The research study will take place in Mackenzie Chown in room D319 with pizza as a light dinner.

There are no known risks associated with this research.

This research may help us to understand whether students would have liked the opportunity of having Earth Sciences as an option in high school, which will increase the probabilities of Earth Sciences degrees at universities. Also, the experiment is to test whether the game is effective or not.

There will be no way to identify individual persons throughout this research. The participants will only give information of their sex and whether they attended a public school or catholic high school. Personal identifiers are not necessary in this study; therefore, your identity will not be revealed in any publication resulting from this study.



Participation in this research study is voluntary. You may refuse to participate or withdraw from the study at any time, and if you decide to withdraw, your information will not be used in the study. You will not be penalized in any way should you decide not to participate or to withdraw from this study.

If you have any questions or concerns about this study or if any problems arise, please contact Mariek Schmidt at Brock University at 905-688-5550, ext. 3527 or mschmidt2@brocku.ca. Also, you can contact Research Ethics Office (reb@brocku.ca (905)688-5550, ext. 3035) who can provide answers to pertinent questions about the research participants' rights.

Please keep a copy of this form for your record.

### **Consent**

**I have read this permission form and have been given the opportunity to ask questions. I give my permission to participate in this study.**

Name (Printed): \_\_\_\_\_

Email address \_\_\_\_\_

Participant's signature \_\_\_\_\_ Date: \_\_\_\_\_

## QUESTIONNAIRE: 'Hebebot: A Martian Expedition to a Terrestrial Analog'

Hello, I am Aileen Williams master's student in the Earth Science Department at Brock University. This questionnaire is designed to obtain feedback of the experiences of the participants who played the interactive game, 'Hebebot: A Martian Expedition to a Terrestrial Analog'. All participants in this survey, will remain anonymous. Thank you for your time and effort.

The questionnaire will be in the form of yes or no and rankings of 1-4, with 4 being the highest.

Male\_\_\_\_, Female\_\_\_\_, Other\_\_\_\_

Education System: Public\_\_\_\_, or Private/Catholic\_\_\_\_

### Part 1: Yes or No

1. Did you like playing technology games?

Yes\_\_\_\_ No\_\_\_\_

2. Was the information shared before the game helpful?

Yes\_\_\_\_ No\_\_\_\_

3. Prior to the game, did you know that Planetary Science was a part of Earth Science?

Yes\_\_\_\_ No\_\_\_\_

4. Were you introduced to any Earth Science in primary or/and secondary school?

Yes\_\_\_\_ No\_\_\_\_

5. Would you have liked to be given the option of Earth Science as a science subject in school?

Yes\_\_\_\_ No\_\_\_\_

### Part 2: Check the box that corresponds to your answer. Use the legend as your guide.

**Legend: 4-Excellent      3-Good      2-Fair      1-Poor**

Questions	4	3	2	1
6. The design and use of information of the game app.				
7. The game led to better understanding of how geology is conducted on Mars.				
8. The instructions of the game were easy to understand.				
9. After the game, you want to know more about future space missions.				
10. The geologic question was answerable with the data provided.				

## Appendix D

LESSON PLAN 1		
<p>Title of the Lesson: Impact Crater</p> <p>Curriculum Area: C2.2 Identify geological features and processes that are common to Earth and other bodies in the solar system (e.g., craters, faults, volcanic eruptions), and create a model or illustration to show these features, using data and images from satellites and space probes.</p> <p>Unit of Study: Earth and Space Science</p>		
<p><b>Background Information:</b> There are circular features on the Moon, Earth and Mars called impact craters formed when impactors(asteroids) smashed into the surface (NASA EG-1997-10-116-HQ). Discuss the theory of the extinction of the dinosaurs.</p>		<p><b>Grouping:</b> Students will work independently and will participate in small group discussions.</p>
<p><b>Learning Expectations:</b> To determine the factors affecting the appearance of impact craters.</p>	<p><b>Assessment:</b> Students will complete a worksheet during the lesson.</p>	
<p><b>Lesson: Follows the ISW Format</b> <i>Bridge-In:</i> Observe and identify the craters in the images.</p> <p><i>Pre-Assessment:</i> Students will compare their hypotheses on ‘what affect the appearance of craters?’</p> <p><i>Participatory Learning:</i> Students will be given the opportunity to participate in the lesson by looking at the video, which allows them to observe the factors which affects impact crater formation. The students will complete a worksheet as they participate in the impact video. Opportunity for short discussions.</p>		<div> <input type="checkbox"/> Mental Set  <input type="checkbox"/> Sharing the Purpose/ Objectives  <input type="checkbox"/> Input  <input type="checkbox"/> Modelling            * Check for Understanding            * Guided Practice            * Independent Practice  <input type="checkbox"/> Closure         </div>
		<p><b>Materials/Resources</b> Work sheet Power point</p>
<p><b>Bloom's Taxonomy:</b> * Knowledge * Understanding <input type="checkbox"/> Application <input type="checkbox"/> Analysis <input type="checkbox"/> Synthesis <input type="checkbox"/> Evaluation</p>	<p><b>Multiple Intelligences:</b> * Linguistic <input type="checkbox"/> Logical/Mathematical <input type="checkbox"/> Spatial <input type="checkbox"/> Musical <input type="checkbox"/> Bodily/Kinesthetic * Interpersonal <input type="checkbox"/> Intrapersonal <input type="checkbox"/> Naturalistic</p>	

LESSON PLAN 2		
<p>Title of the Lesson: Maar Craters</p> <p>Curriculum Area: C2.2 Identify geological features and processes that are common to Earth and other bodies in the solar system (e.g., craters, faults, volcanic eruptions), and create a model or illustration to show these features, using data and images from satellites and space probes.</p> <p>Unit of Study: Earth and Space Science</p>		
<p><b>Background Information:</b>  Maars are depressions in the ground created by a volcanic eruption. They resemble impact craters. Most Maars are not seen because of weathering and erosion, and some maars are filled with water as lakes (Valentine &amp; Graetinger, 2016).</p>		<p><b>Grouping:</b>  Students will work independently and will participate in small group discussions.</p>
<p><b>Learning Expectations:</b>  Students will be able to explain how a maar is formed and be able to identify the features.</p>	<p><b>Assessment:</b>  Students will complete a worksheet during the lesson.</p>	
<p><b>Lesson: Follows the ISW Format</b>  <i>Bridge-In:</i> students will look at an image of a maar and a scoria cone and list the differences and how they think each were formed.</p> <p><i>Pre-Assessment:</i> Students will discuss the interaction when hot oil and water mixes, after looking at an image.</p> <p><i>Participatory Learning:</i> Students will participate in the lesson by looking at a short video of a maar formation. They will work in pairs to explain how a maar is formed, by looking at 5 images in chronological order. Students will compare impact craters and maar craters.</p>		<div> <input type="checkbox"/> Mental Set  <input type="checkbox"/> Sharing the Purpose/Objectives  <input type="checkbox"/> Input  <input type="checkbox"/> Modelling  * Check for Understanding  * Guided Practice  * Independent Practice  <input type="checkbox"/> Closure </div>
		<p><b>Materials/Resources</b>  Computer  Worksheet</p>
<p><b>Bloom's Taxonomy:</b>  * Knowledge  * Understanding  <input type="checkbox"/> Application  <input type="checkbox"/> Analysis  <input type="checkbox"/> Synthesis  <input type="checkbox"/> Evaluation</p>	<p><b>Multiple Intelligences:</b>  * Linguistic  <input type="checkbox"/> Logical/Mathematical  <input type="checkbox"/> Spatial  <input type="checkbox"/> Musical  Bodily/Kinesthetic  *Interpersonal  <input type="checkbox"/> Intrapersonal  <input type="checkbox"/> Naturalistic</p>	

### LESSON PLAN 3

Title of the Lesson: Operating a Planetary Rover

Curriculum Area: C2.2 Identify geological features and processes that are common to Earth and other bodies in the solar system (e.g., craters, faults, volcanic eruptions), and create a model or illustration to show these features, using data and images from satellites and space probes.

Unit of Study: Earth and Space Science

**Background Information:**

NASA uses artificial intelligence on the rovers to unravel the many mysteries of space. Rovers are equipped with many cameras and tools which can analyze rocks and the morphology on Mars (Klug, Mars K-12 Education Outreach Program).

**Grouping:**

Students will work in small groups

**Learning Expectations:**

Students will understand the operations of the rover on Mars.

**Assessment:**

Students will play the game Hebebot: A Martian Expedition to a Terrestrial Analog.

**Lesson: Follows the ISW Format**

*Bridge-In:* Students will be shown a picture of a rover, the arm and a rock sample. Students will discuss how the rover would pick up the rock.

*Pre-Assessment:* Students will discuss the skills necessary for the rover to operate on Mars.

*Participatory Learning:* Students will be placed in groups as they complete a task of retrieving an item by mimicking the traverse of a rover (Klug, Mars K-12 Education Outreach Program).

- ☐ Mental Set
- ☐ Sharing the Purpose/ Objectives
- ☐ Input
- ☐ Modelling
- \* Check for Understanding
- \* Guided Practice
- \* Independent Practice
- ☐ Closure

**Materials/Resources**

Blind folds, balls, containers, game instructions

**Bloom's Taxonomy:**

- \* Knowledge
- \* Understanding
- \* Application
- ☐ Analysis
- ☐ Synthesis
- \*Evaluation

**Multiple Intelligences:**

- ☐ Linguistic
- \* Logical/Mathematical
- ☐ Spatial
- ☐ Musical
- \*Bodily/Kinesthetic
- \* Interpersonal
- ☐ Intrapersonal
- ☐ Naturalistic

## WORKSHEET

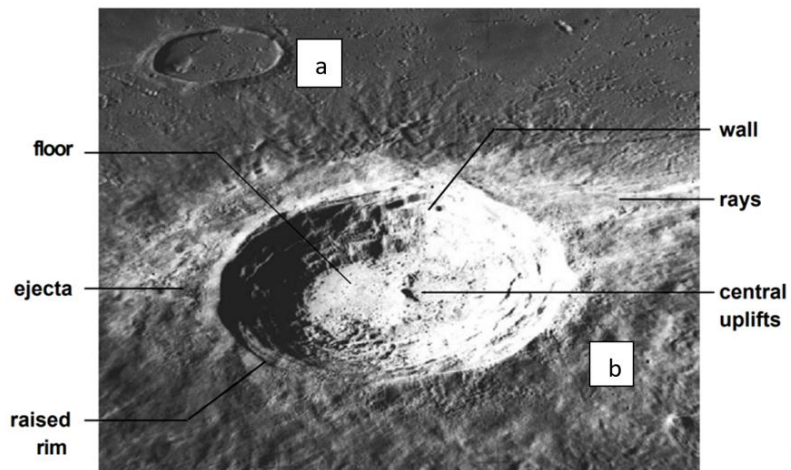
### IMPACT CRATERS

Complete the following questions

1. What affects the appearance of impact craters?
2. During the video, observe what happens when the:

15g ball hits the flour	30g ball hits the flour	60g ball hits the flour

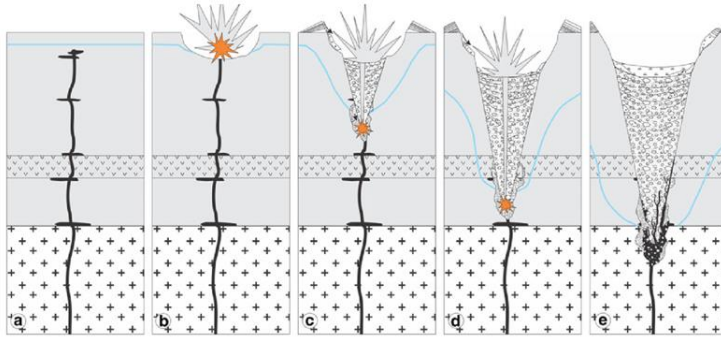
3. If asteroids formed crater a and b in the image below, what factors could cause crater b to be deeper and wider than crater a?



## WORKSHEET

### MAAR CRATERS

1. Explain how a maar is formed by looking at the pictures from a- e. The blue line represents the water source, the black vertical line represents magma coming to the surface.



- a)
- b)
- c)
- d)
- e)

## **WORKSHEET**

### **ROVER -- A game for two players**

Set up an obstacle course using objects such as chairs and stools and try this fun game. The player will navigate a human robot around the obstacles and learn about the intricacies of programming a robot.

Objective of the game: Use verbal commands to guide a human robot around different obstacles without bumping into objects. At the end of the obstacle course, a player will command the robot to drop a ball into a container.

#### **Equipment:**

- Blindfold
  - Container
  - ball
1. Choose one player to be the robot.
  2. The second player will control the robot.
  3. Place the blindfold securely on the robot.
  4. Give the ball to the robot.
  5. Set up a small obstacle course using furniture. You may arrange pieces of paper on the floor to create an obstacle course.
  6. The robot will follow verbal instructions given by the controller to move along the prescribed course and then deposit the ball in the container.
  7. The robot cannot talk and must follow the directions exactly as given.
  8. After the robot has successfully put the ball in the container, the robot and controller switch roles and try again.

#### **Safety Hint:**

If the controller sees the robot headed toward something that could cause an injury, stop the game immediately.

#### **Exact Hints:**

**Controller Hint:** Use detailed instructions "Turn body right," not "turn right." Give exact number of steps.



## PowerPoint Slides- read left to right

### Welcome and thank you!

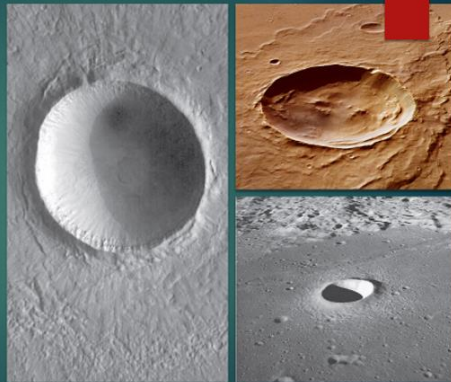
- ▶ Principal investigator: Mariek Schmidt PhD supervisor
- ▶ Student investigator: Aileen Williams
- ▶ Please sign the consent form
- ▶ Objective: To test the efficiency of the game application: "Hebebot: A Martian Expedition to a Terrestrial analog."
- ▶ Information will be presented on:
  1. impact craters
  2. maar volcanoes
  3. operations of a Martian rover
- ▶ The game will be played
- ▶ Complete a 5 minutes questionnaire

## Impact Crater

TO DETERMINE THE FACTORS AFFECTING THE APPEARANCE OF  
IMPACT CRATERS.

### Can you identify the features in the pictures?

- ▶ Left image: Moltke Crater on the Moon (Apollo 11); 6.5 km across, 1.3 km deep.
- ▶ Top right Image: Melas Dorsa impact crater on Mars (G. Neukum/ESA, DLR, FU Berlin)
- ▶ Bottom right Image: Crater on Mars (Mars Global Surveyor)



### Background Information

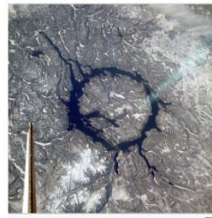
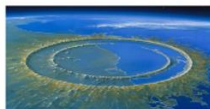
- ▶ There are circular features on the Moon, Mars and Earth and other moons called impact craters
- ▶ Formed when impactors smashed into the surface (asteroids)
- ▶ The explosion and excavation of materials at the impacted site created piles of rock (called ejecta)
- ▶ around the circular hole as well as bright streaks of target material (called rays) thrown for great distances.



2018 Asteroid RC 6 barreling towards Earth (image: GETTY 2018)

## Impact Craters on Earth

- ▶ On Earth, impact craters are not as easily recognized because of weathering and erosion.
  - ▶ Famous impact craters on Earth are
    - Meteor Crater in Arizona, U.S.A.
    - Manicouagan in Quebec, Canada;
    - Sudbury in Ontario, Canada;
    - Reis Crater in Germany;
    - Chicxulub on the Yucatan coast in Mexico.
- Chicxulub is considered by most scientists as the source crater of the catastrophe that led to the extinction of the dinosaurs at the end of the Cretaceous period. An interesting fact about the Chicxulub crater is that you cannot see it. Its circular structure is nearly a kilometer below the surface and was originally identified from magnetic and gravity data.



The crater in winter, as seen from the space shuttle (north is to the lower right)

## Impact Crater activity

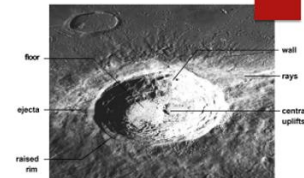
- ▶ [Create hypothesis](#) what affects the appearance of impact craters?
- ▶ Demonstration
- ▶ Complete the worksheet while looking at the video
- ▶ [Impact Crater video](#)

## Cont. impact crater

- ▶ The factors affecting the appearance of impact craters are
  - a) the **size** and **velocity** of the impactor
  - b) and the **geology** of the target surface

## Features of Impact Craters

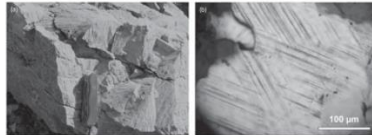
A Teacher's Guide with Activities, NASA EG-1997-10-116-HQ



- raised rim** - rock thrown out of the crater and deposited in a ring-shaped pile of debris at the crater's edge during the explosion and excavation of an impact event.
- floor** - bowl shaped or flat, characteristically below surrounding ground level unless filled in with lava.
- central uplifts** - mountains formed because of the huge increase and rapid decrease in pressure during the impact event. They occur only in the center of craters that are larger than 40 km diameter. See Tycho crater for another example.
- walls** - characteristically steep and may have giant stairs called terraces.
- ejecta** - blanket of material surrounding the crater that was excavated during the impact event. Ejecta becomes thinner away from the crater.
- rays** - bright streaks starting from a crater and extending away for great distances. See Copernicus crater for another example.

## Features of impact craters

- Image a) shatter cones (thin hair-like strands) in limestone from the Haughton impact structure in Canada.
- Image b) microscopic planar deformation of the glass in the quartz (Osinski et al., 2006).



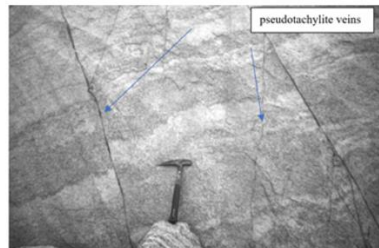
## Features of impact craters

- Image a) aerial view of the 80 m high cliffs of the Mistastin impact structure, Labrador, Canada. The white streaks in the middle of the image are the impact melts.
- b) fine grained impact melt rock from the Discovery Hill locality, Mistastin impact structure (Osinski et al., 2006)



## Features of impact craters

- Image of pseudotachylite veins in a granitic rock Parys, South Africa. Rock hammer for scale (Melosh, 2005).



# Maar Craters

STUDENTS WILL BE ABLE TO ILLUSTRATE AND EXPLAIN THE KEY FEATURES OF A MAAR

What happens when you mix heated oil and water?

Explosion!!!



Which one is a volcano?

What is a maar?

- ▶ A maar is an opening into the ground with the floor lying below the eruptive surface
- ▶ Maar are formed by phreatomagmatic explosions: interaction of **magma** and **groundwater**
- ▶ Maar-diatremes are the second most common volcano type on continents and islands

▶ Top image: Alaska Maar. Photo by MysteriousAll 2013  
▶ Bottom image: Eifel Volcanic field Germany, Holzmaar Photo by: geopark-vulkan@el.de

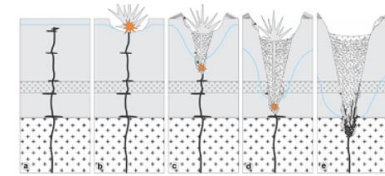


## Maar formation videos

- ▶ <https://youtu.be/Hdow0Oh5MEI>
- ▶ <https://youtu.be/n6dDesUPkMo>

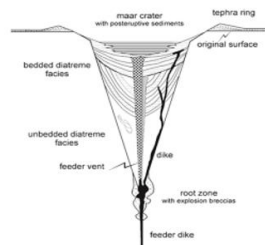
## Maar formation activity

- ▶ In pairs explain how a maar is formed. The blue line represents water.



## Maar features

- ▶ Crater –an open space
- ▶ Tephra rings-The tephra rings are made up of pyroclastic deposits of bedded and cross-bedded tuffs and lapilli tuffs
- ▶ Most of the rocks are volcanic, dark in color, basalts-Silica ( $\text{SiO}_2$ ) content - 45%-52%.



## Features of Maars

- ▶ Image showing tuff beds on the crater rim.





## Features of Maars

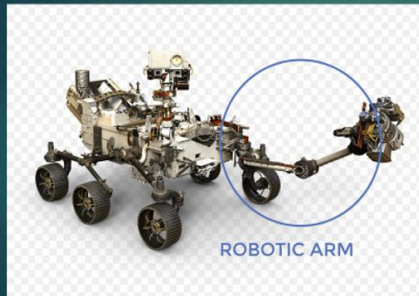
- Image showing stratified layers of ash and scoria piles



## Rover

OPERATING A PLANETARY ROVER

## How did this robot pick up this rock?



## Introduction to Mars Rovers

- A Mars rover is an automated motor vehicle which propels itself across the surface of Mars after landing.
- NASA's Mars Exploration Rover Mission is an ongoing robotic mission
- Objectives:
  - Determine whether life ever arose on Mars
  - Characterize the climate on Mars
  - Characterize the geology of Mars
  - Prepare for human exploration

## Curiosity

- ▶ The spacecraft launched from Cape Canaveral, Florida, on Nov. 26, 2011, and arrived on Mars on Aug. 6, 2012
- ▶ The car-size Curiosity rover \$2.5 billion
- ▶ Curiosity's main goal is to assess whether Mars is capable of supporting microbial life/habitability
- ▶ Photo Credit: NASA/JPL-Caltech



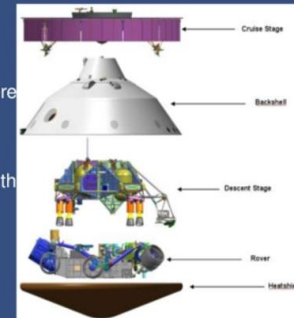
To get to Mars, Curiosity will travel safely tucked inside a Aerospace shell.

**Cruise stage:** Propulsion systems.

**Back shell:** Parachute systems

**Descent stage:** Will provide rocket-powered deceleration to prepare for the rover to touch down on the surface of Mars.

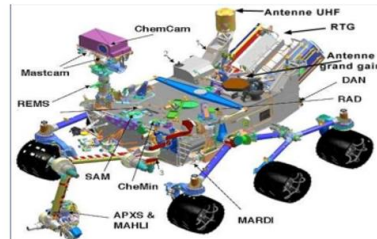
**Heat Shield:** Will protect rover from heat that occurs due to the friction of atmosphere.



P.Sampath Kumar, 2013

## Scientific instruments on the rover

- ▶ Mast Camera (MastCam) Chemistry and Camera complex (ChemCam)
- ▶ Rover Environmental Monitoring Station (REMS) Hazard avoidance cameras (hazcams)
- ▶ Mars Hand Lens Imager (MAHLI) Alpha Particle X-ray Spectrometer (APXS) Chemistry and Mineralogy (CheMin)



## Activity

- ▶ Factors which affects the rovers operations: dust storms cause damage the rover and obscure visibility
- ▶ Terrain, rovers can get stuck, causing damage to the wheels
- ▶ What skills are needed to operate a rover?
- ▶ Students will be placed in groups to conduct a mini experiment to find out the skills needed to operate their expedition.

